NASA Technical Paper 3059

March 1991

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Symbols and Acronyms

ACC	advanced carbon-carbon
ALS	Advanced Launch System
APAS	Aerodynamic Preliminary Analysis System
APU	auxiliary power unit
AVID	Aerospace Vehicle Interactive Design
C_D	drag coefficient
C_L	lift coefficient
CH_4	methane fuel
DDT&E	design, development, testing, and evaluation
DOD	Department of Defense
ETR	Eastern Test Range
FSTS	Future Space Transportation Study
GLOW	gross lift-off weight, lb
g	acceleration due to gravity, 32.2 ft/sec^2
IOC	initial operating capability
I_{sp}	specific impulse, sec
LEO	low Earth orbit
LH_2	liquid hydrogen
LOX	liquid oxygen
MER	mass estimating relation
NASP	National Aero-Space Plane
OMS	orbital maneuvering system
P/A module	propulsion and avionics module
POST	Program To Optimize Simulated Trajectories
RCS	reaction control system
RP	rocket propellant (hydrocarbon)
SDI	Strategic Defense Initiative
SRB	solid rocket booster
SSTO	single stage to orbit
STAR	Space Taxi and Recovery (vehicle)
STAS	Space Transportation Architecture Study
STBE	Space Transportation Booster Engine
STME	Space Transportation Main Engine
STS	Space Transportation System (current Shuttle)
S II	Shuttle II
T/W	thrust-to-weight ratio

Ti/Al	titanium-aluminide
TPS	thermal protection system
WTR	Western Test Range
α	angle of attack, deg
γ	relative flight-path angle, deg

Summary

This report presents a series of trade studies conducted between 1986 and 1988 on a complementary architecture of launch vehicles as a part of a study often referred to as "Shuttle II." The results of the trade studies performed on the vehicles of a reference Shuttle II mixed-fleet architecture have provided an increased understanding of the relative importance of each of the major vehicle parameters. As a result of trades on the reference booster-orbiter configuration with a methane booster, the study showed that 60 percent of the total lift-off thrust should be on the booster and 40 percent on the orbiter. It was also found that the lift-off thrust-to-weight ratio (T/W) on the booster-orbiter should be 1.3. This leads to a low dry weight and still provides enough thrust to allow the design of a heavy-lift architecture. As the result of another trade study, the dry weight of the reference booster-orbiter configuration was found to be a minimum for a staging Mach number between 5.5 and 6; however, a staging Mach number of 3 was chosen for a variety of operational considerations. Other trade studies on the booster-orbiter vehicle demonstrate that the crossfeeding of propellant during boost phase is desirable and that engine-out capability from launch to orbit is worth the performance penalty. Technology assumptions made during the Shuttle II design were shown to be approximately equivalent to a 25-percent across-the-board weight reduction over Space Shuttle technology. The vehicles of the Shuttle II architecture were also sized for a wide variety of payloads and missions to different orbits.

Many of these same parametric trades were also performed on completely liquid-hydrogen-fueled fully reusable concepts. If a booster-orbiter vehicle is designed to use liquid hydrogen engines on both the booster and orbiter, the total vehicle dry weight is only 3.0 percent higher than the reference dual-fuel booster-orbiter, and the gross weight is 3.8 percent less. For this booster-orbiter vehicle, a lift-off T/W of 1.3, a thrust split of about 60 percent on the booster, and a staging Mach number of 3 all proved to be desirable. This modest dry weight increase for a liquid-hydrogen-fueled Shuttle II system should be more than offset by the elimination of the entire hydrocarbon engine development program and the savings in operation costs realized by the elimination of an entire fuel type.

This paper presents the reference Shuttle II vehicle concepts and the results of a series of parametric trade studies performed on those vehicles. In each trade discussed, special attention is given to the major vehicle performance and operational issues involved.

Introduction

An initial examination of civilian and military space launch requirement studies for the post-1990 era (refs. 1 and 2) determined that anticipated missions tend to fall within two main categories. On one hand there is the need to move large masses—bulk cargo, propellants, and large satellites—to orbit at the lowest possible cost or low dollars per pound; but for priority or sortie types of missions involving personnel transport, servicing, and repair visits, a low dollars per flight approach is a valid consideration. (See ref. 3.) Based on these payload requirement studies, the manned, priority/sortie Shuttle II reference vehicle was designed to have the capability to launch and return 12 000 lb of payload to a polar parking orbit (98° inclination, 150 nmi circular) and to launch at least 20 000 lb of payload to the space station (28.5° inclination, 262 nmi circular) as an initial baseline. Initial payload insertion to this polar parking orbit allows for subsequent transfer to a 98° inclination, 270 nmi circular Sun-synchronous orbit. Additional requirements were a baseline cylindrical payload bay size that is 15 ft in diameter and 30 ft in length to assure compatibility with current Space Shuttle payloads and a capability of accommodating a crew of two to five persons for mission durations from 2 to 5 days. To satisfy the requirements of low dollars per pound, the study of a phased vehicle architecture was also initiated. Included in this architecture is a heavy-lift launch vehicle capable of launching 100 000 lb of payload to LEO (low Earth orbit) by the mid-1990's and 150 000 lb of payload to LEO by the late 1990's.

The Shuttle II study has been independent of, yet complementary to, the Space Transportation Architecture Study (STAS), which was established by Presidential Directive in 1985 and completed in 1987. (See ref. 4.) The STAS studies were conducted by four major aerospace contractors to examine, in detail, future space transportation requirements, system options, and technology requirements.

Initially, many studies were performed considering the relative capabilities and impacts on life-cycle costs of a variety of vehicle types: single-stage versus two-stage vehicles, rocket-powered versus air-breathing vehicles, and horizontal- versus vertical-takeoff vehicles. The operability, reliability, and safety requirements for each of these types of vehicles were considered. The role of technology in comparing each of these vehicles was also important. Various levels of technology were examined, and it was concluded that, for a projected normal-growth technology level consistent with a 1992 development cycle start date, the two-stage, rocket-powered, vertical-takeoff system was the most reasonable alternative for a Shuttle II reference vehicle to be studied in greater detail. It is interesting to note that the four major STAS contractors all came to the same conclusion as the Shuttle II vehicle design team. Although they disagreed on what the baseline (reference) mission should be for a next-generation launch system, they all agreed that it should be a two-stage, vertical-takeoff, rocket-powered system with an appropriate heavy-lift companion vehicle. (See ref. 4.)

As a part of the Shuttle II study, a series of parametric trade studies was begun to optimize the reference dual-fuel fully reusable system and associated architecture. These trades also include the design and optimization of a liquid-hydrogen-fueled Shuttle II system and architecture. Vehicles were designed with lift-off thrust-to-weight ratio, staging Mach number, and thrust split between the booster and orbiter engines as parameters that were varied in an attempt to determine the optimal system. Other major vehicle parameters and systems investigated include the level of technologies employed, type of booster propellant, crossfeeding of propellants, engine-out capability, payload parametric sizing, and inclination of the target orbit. In the optimization of each of the Shuttle II vehicles, a design-for-operations approach was employed to minimize manpower and facility requirements and turnaround time.

As mentioned above, an attempt was made in this study to *optimize* the reference Shuttle II architecture through a series of parametric trade studies. Throughout this paper an *optimal* system will refer to one that fulfills the mission requirements, subject to certain safety, reliability, and operations constraints, for the lowest estimated total cost. The primary parameter used in this study to reflect production costs is vehicle dry weight (i.e., the weight of the vehicle without payload, propellant, crew, or residual fluids). The primary parameters used to reflect operation costs are perceived manpower, facility, and turnaround time requirements. System safety and reliability are treated strictly in a qualitative manner. Parametric trades are performed to determine the quantitative effect of incorporating particular systems (e.g., crew escape and engine-out) that contribute to safety and reliability, then qualitative decisions are made to either incorporate a particular system or not.

Tools and Methods

The performance of the vehicle trade studies to be presented in this paper was facilitated by many computing tools for conceptual and preliminary launch vehicle design. Most of the individual software tools used in each phase of vehicle design have been incorporated into a single system that uses a menu-driven executive called the Aerospace Vehicle Interactive Design (AVID) system. The AVID system is a computer-aided design system that was developed for the conceptual and preliminary design of aerospace vehicles. AVID has evolved gradually from the original concept described in reference 5.

The AVID executive facilitates the integration of independent analysis programs into a design system where the programs can be executed individually for analysis or executed in groups for design iterations and parametric trade studies. Currently, the programs that have been integrated into the AVID system for launch vehicle design include geometry, weights/sizing, aerodynamics, propulsion, flight performance, and aerodynamic heating. Most of these individual software elements have been developed inhouse or by contract. Many of these, like the APAS (Aerodynamic Preliminary Analysis System) aerodynamics package (ref. 6) and the POST (Program To Optimize Simulated Trajectories) trajectory program (ref. 7), have become widely used by many major aerospace contractors. The two major software elements used to perform the principal design trades on the reference Shuttle II architecture are the AVID weights/sizing program and POST.

Design Tools

AVID Weights/Sizing Program

The current AVID weights/sizing package has evolved over the last few years into a flexible, easy-to-use program. It utilizes various empirical mass-estimating relations (MER's) based on historical data where possible. Often these MER's are heavily dependent on Space Shuttle subsystem masses and the properties and densities of the material used in a particular structure. Typical AVID weight statements for the reference Shuttle II booster, orbiter, and core vehicles are given in appendix A, and the MER's used for each of the reference Shuttle II vehicles are provided in appendix B. A typical MER obtained for the landing gear of a winged aerospace vehicle is of the form

$$Y = K \times (\text{Landed mass})^c \times (1 - \text{RED})$$

where K and c are empirical constants, and RED is a technology reduction factor. Special care must be taken by the researcher in arriving at suitable MER's. In particular, each data point included in the regression analysis should be appropriate for use in estimating masses for the particular vehicle under design so that a consistent set of data is utilized. This type of regression approach is quite useful for estimating many subsystem weights. When using these historical MER's for the design of advanced transportation systems like those in the Shuttle II study, it is often necessary to account for weight reductions that may be obtained through technology advances (e.g., more extensive use of titanium and composite materials, advanced avionics). This can easily be accomplished by multiplying each mass-estimating equation by an appropriate constant.

A given vehicle geometry is modeled in the AVID weights/sizing program by a set of reference volumes, areas, and lengths with the use of appropriate equations. This reference geometry is then scaled geometrically by using a sizing loop to converge on a particular mass ratio, which is the ratio of total vehicle gross weight to injected or burnout weight. Some large vehicle components, like wings and body structure, have much more complex mass-estimating equations that are highly dependent on the geometry of the particular vehicle. Because of the great dependence of the mass-estimating process on a given geometry and vehicle type, weights and sizing programs tend to be very vehicle dependent. Although the original AVID weights/sizing software was designed for winged, two-stage, reusable vehicles, the same techniques and structure have also been applied to model other types of launch vehicles.

The propulsion systems used in the AVID weights/sizing program are usually obtained from the results of studies by engine contractors or from inhouse studies. These engine weights are modeled primarily as functions of vacuum thrust. Hence, the reference engines are scaled up or down in the sizing process as required for the thrust requirements of a particular vehicle.

POST Trajectory Program

The Program To Optimize Simulated Trajectories (POST) is a three-degree-of-freedom generalized point mass, discrete parameter targeting, and optimization program. (See ref. 7.) POST allows the user to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. The simulation flexibility of the program is achieved by decomposing the trajectory into a logical sequence of simulation segments, or phases. By segmenting the mission into phases, each phase can be modeled and simulated in the manner most appropriate for that particular flight regime. This flexible simulation capability is augmented by a discrete parameter optimization capability that includes equality and inequality constraints. (See ref. 8.)

Design Methods

The conceptual and preliminary design of a launch vehicle is a complex, iterative procedure requiring the synthesis of a wide variety of engineering disciplines. The aforementioned AVID system greatly expedites the design process by integrating independent analysis programs from various disciplines. A reference vehicle is obtained to fulfill a given mission only after repeated iterations between analysts in the areas of geometry, aerodynamics, packaging, weights/sizing, ascent and entry trajectories, and aerodynamic heating. To obtain an initial reference vehicle, one must assume certain initial values for various vehicle parameters in the process (such as vehicle thrust-to-weight ratio, staging Mach number, thrust split between booster and main engines). Once this baseline vehicle is defined, these parameters can then be varied in an attempt to better understand the role that each one plays in the design process and to determine the optimal system to perform the required mission. For each component of the Shuttle II architecture, an initial reference vehicle was designed and parametric trades were conducted. The reference vehicles presented in this paper are the result of these trades.

The major trade studies on the Shuttle II system presented here require only the use of POST and the AVID weights/sizing program. For example, to see how a variation in lift-off thrust-to-weight ratio (T/W) affects the reference two-stage, booster-orbiter configuration, the necessary modifications to the weights program must first be made to account for a new T/W. Then one must assume initial values for the mass ratio, which is the ratio of gross lift-off weight (GLOW) to burnout or injected weight, of the booster and orbiter. The weights/sizing program then provides a weight statement of the booster-orbiter configuration corresponding to these mass ratios. Since the weights and sizing process geometrically scales the vehicle up and down, the aerodynamic constants (variation of C_D and C_L with angle of attack and Mach number) do not change significantly; only the reference areas change. Then, the POST program is used with appropriate weights, reference areas, and engine constants to obtain new mass ratios. In a typical launch vehicle ascent trajectory, the vehicle is controlled by specifying pitch rate events at a number of phases throughout the trajectory. The conditions to be targeted at the end of the trajectory are specified as the desired velocity, altitude, and flight-path angle. The trajectory is then targeted and optimized within typical constraints on acceleration, angle of attack, dynamic pressure, wing normal force, and staging Mach number, where the optimized variable is typically the maximum injected weight relative to a fixed lift-off weight. These refined mass ratios are inserted in the weights program and the same process is repeated until convergence of the mass ratios is achieved. This method can then be repeated for other values of T/W until enough design points are obtained to determine how the reference vehicle changes with variations in lift-off T/W. Note that each design point represents an actual converged vehicle design using this method.

Baseline Vehicle Concepts

Reference Architecture

The purpose of the phased architecture portion of the Shuttle II study was to design a heavy-lift transportation vehicle to complement the manned, two-stage, priority/sortie vehicle and to provide an evolutionary growth path for such a system. As the study began, the intent was to integrate these two systems into a common architecture—sharing common launch sites, operational facilities, and manpower—to greatly reduce life-cycle costs. (See ref. 9.) This common element approach is facilitated by the sharing of the same reusable glide-back booster between the Shuttle II orbiter and heavy-lift core vehicles as shown in the completed architecture in figure 1.

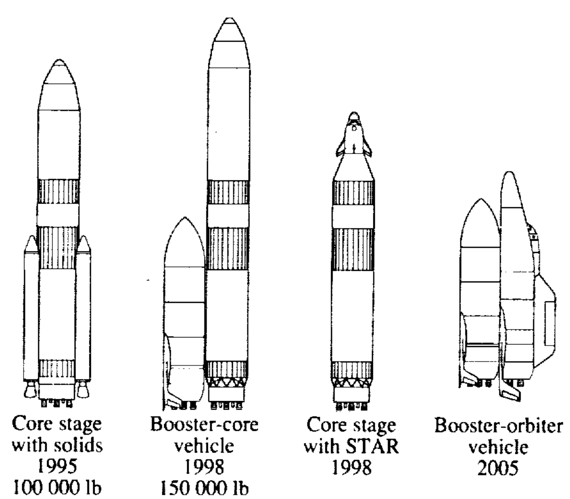

Figure 1. Shuttle II reference architecture.

As shown in figure 1, under this phased approach, the heavy-lift core vehicle would be developed first. Augmented with three solid rockets, this core would provide an interim capability of 100 000 lb of payload to LEO in the mid-1990's. The next step would be to develop the Shuttle II unmanned glide-back booster by the late 1990's to replace the solid rocket boosters. This reusable booster would be used in conjunction with the core vehicle, with crossfeeding of propellants, to inject payloads of up to 150 000 lb to LEO. Key elements in this phased development are the design, development, test, and evaluation (DDT&E) of the glide-back booster and the recoverable propulsion and avionics (P/A) module to be used with the heavy-lift core stage. After orbital insertion of the core stage and payload, this P/A module would separate from the core stage and reenter the atmosphere to allow the recovery of the expensive propulsion system and avionics hardware. Another feature of the architecture shown in figure 1 is the Space Taxi and Recovery (STAR) vehicle which could be used with the core vehicle in the late 1990's. (See ref. 3.) This small vehicle could assure manned access to space if the Space Shuttle or Shuttle II booster-orbiter were unavailable. It also could be configured to allow space station crew rotation or emergency return capabilities. Finally, shortly after the turn of the century, the fully reusable booster-orbiter would be introduced to gradually replace an aging Space Shuttle fleet.

The following sections summarize the major characteristics of each of the components of the reference Shuttle II architecture. Varying levels of technology are assumed for each of these vehicles depending on the vehicle schedule and type. These reference vehicles incorporate the results of the series of trade studies to be presented.

Booster-Orbiter Vehicle

Shown in figure 2 is the reference manned, reusable Shuttle II booster-orbiter system. It is designed to perform priority- or sortie-class missions involving personnel transport, on-orbit servicing and repair, and transportation to and from orbit of

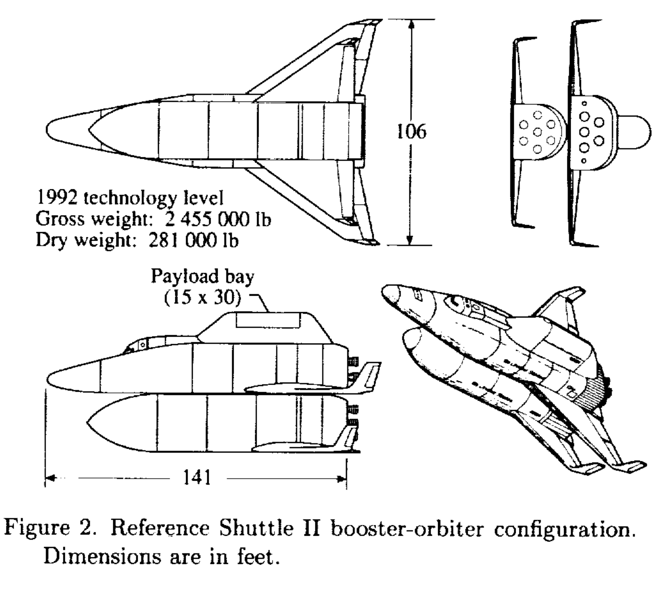

Figure 2. Reference Shuttle II booster-orbiter configuration. Dimensions are in feet.

high-valued payloads and supplies. These capabilities are enhanced via the detachable payload container concept, illustrated in figure 3, which could reduce turnaround time and operation costs. (See ref. 9.) Additional characteristics are shown in figure 4, and a set of trajectory plots for the baseline mission of 12 000 lb to polar orbit are included in appendix C. Also, as mentioned previously, a weight statement of this vehicle is provided in appendix A. Designing the booster-orbiter vehicle to carry 12 000 lb to polar orbit provides the capability of carrying 37 000 lb to the space station. As a result of various trade studies, this vehicle has a lift-off thrust-to-weight ratio (T/W) of 1.3, stages at a Mach number of 3, and has a thrust split of 60 percent on the booster and 40 percent on the orbiter. The rocket engines used in the Shuttle II study are based on the results of the STME (Space Transportation Main Engine) and STBE (Space Transportation Booster Engine) studies performed for the Marshall Space Flight Center. (See refs. 10 and 11.) The purpose of these studies is to determine what sort of operationally efficient reusable propulsion systems can be developed for use on next-generation space transportation systems. The booster is methane fueled and uses six STBE-type engines with a vacuum specific impulse I_{sp} of 369 sec and a vacuum thrust level of 359 500 lb each. The orbiter is liquid-hydrogen fueled and uses five STME-type engines with a vacuum I_{sp} of 441 sec and a vacuum thrust level of 311 500 lb each. Additional engine characteristics are provided in table 1.

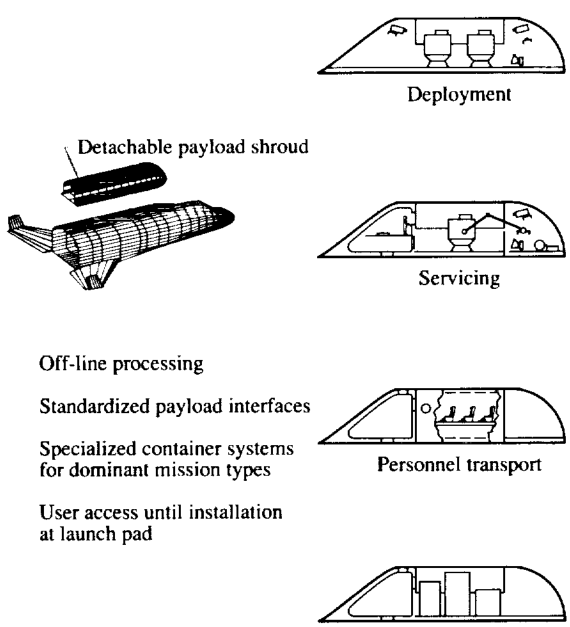

Figure 3. Detachable payload container system.

IOC: 2005

Payloads:
37000 lb to 28.5°/262 nmi
12000 lb to 98°/150 nmi

GLOW: 2 455 000 lb

Max acceleration: 3g

Injection orbit: 50 x 100 nmi

Height: 141 ft

STAR vehicle may be substituted for normal delivery/servicing canisters; this provides for personnel transport (6 + crew of 2) and an independent launch escape capability

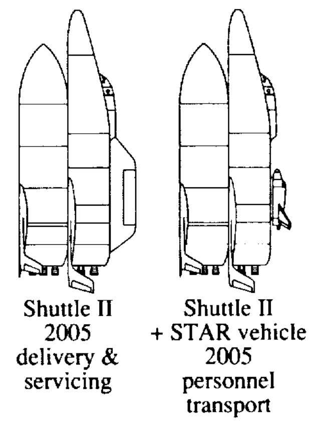

Figure 4. Characteristics of booster-orbiter configuration.

Table 1. Characteristics of Reference STME-Type and STBE-Type Engines

Engine parameter	STME type	STBE type
Vacuum thrust, lb	311 500	359 500
Vacuum I_{sp}, sec	441	369
Weight, lb	4030	3770
Area ratio	60	55
Flow rate, lb/sec	706.3	974
Propellants	LOX/LH_2	$LOX/CH_4/LH_2$
Mixture ratio (inlet)	6.0	3.47

Both the booster and the orbiter have engine-out capability, which means that a booster engine and an orbiter engine could both malfunction at any time from launch until orbital insertion, be shut down, and the vehicle could still attain orbit and fulfill its mission. The booster crossfeeds LOX/LH_2 propellant to the orbiter engines during the boost phase; hence, the orbiter is completely filled with propellants at staging. The booster then glides back to the launch site after staging as shown in figure 5. In addition, the orbiter includes a crew escape system illustrated in figure 6. This crew escape system represents a significant portion (2400 lb) of the vehicle dry weight. In fact, having crew escape provisions leads to a 12-percent reduction in booster-orbiter payload capability. The booster and orbiter both land at a speed of 175 knots, and the orbiter has a crossrange capability of 1100 nmi on entry to allow once-around abort from orbit for a polar launch.

The major structural technologies assumed for the Shuttle II booster and orbiter are summarized

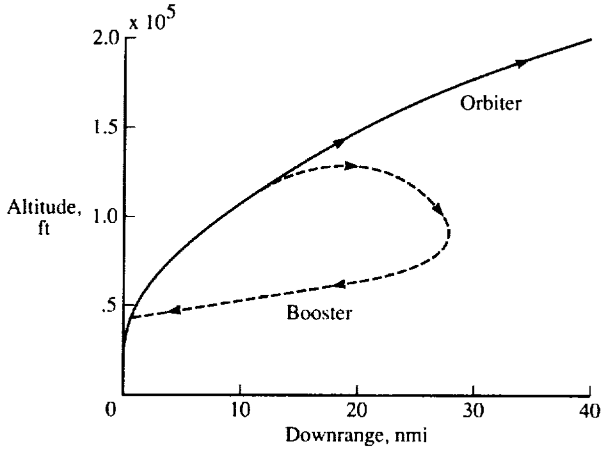

Figure 5. Glide-back booster trajectory for reference booster-orbiter launch from WTR. Staging conditions: Time = 114 sec; Mach 3; Altitude = 100 200 ft; $\gamma = 40.3°$.

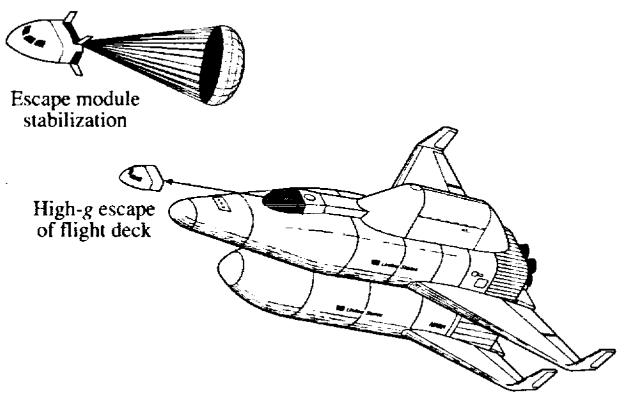

Figure 6. Crew emergency escape system.

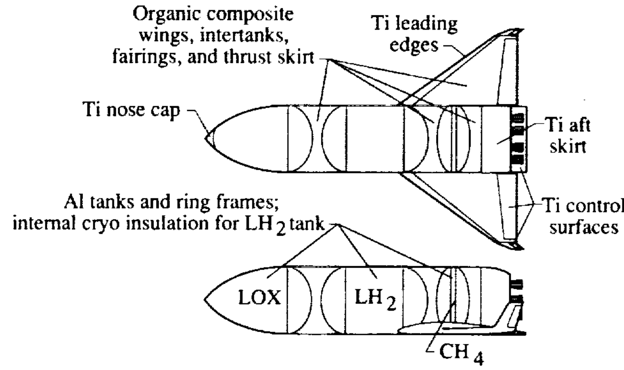

Figure 7. Primary structural technology assumptions for reference Shuttle II booster.

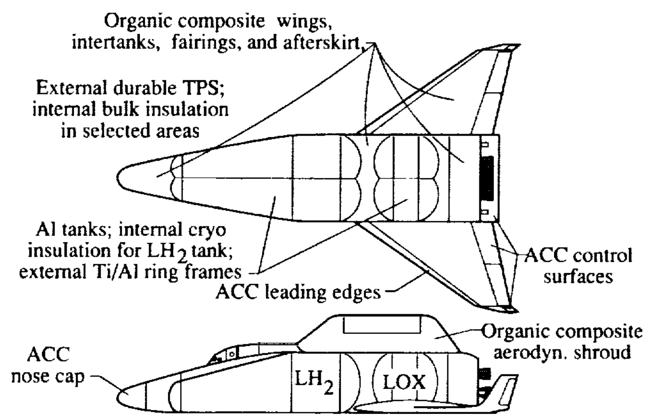

Figure 8. Primary structural technology assumptions for reference Shuttle II orbiter.

in figures 7 and 8. Reusable cryogenic tankage is a critical technology for the development of any fully reusable launch system. The Shuttle II booster and orbiter employ high-strength aluminum cryogenic tankage using advanced construction techniques, and a weight factor of 10 percent is added to account for tank reusability. Organic composites are employed for wings, intertanks, fairings, and skirts. The orbiter employs an advanced carbon-carbon (ACC) nose cap, leading edges, and control surfaces and a durable external thermal protection system (TPS). The booster, which remains in a benign heating environment, employs a titanium nose cap, leading edges, and control surfaces and no external TPS.

As mentioned earlier, the aerodynamics for the booster-orbiter configuration, which act as inputs to POST, were computed with the APAS aerodynamics package (ref. 6). Further details on APAS and plots of some of the aerodynamic characteristics of the booster-orbiter configuration are presented in appendix D. Note that the Shuttle II booster and orbiter aerodynamics were each evaluated independently in APAS, and the aerodynamic forces from each vehicle were added together linearly in POST. Hence, no aerodynamic interference effects, which would result from the bodies being mated in close proximity, are taken into account.

From the outset of the study, the importance of a next-generation launch system being designed for operations to reduce life-cycle costs (which are the sum of DDT&E and recurring costs) has been emphasized. Over 45 percent of the recurring costs of the current, partially reusable Space Transportation System (STS) are associated with operations (i.e., refurbishment, integration, inspection, and launch of the vehicle), and the recurring costs account for 73 percent of the total life-cycle costs of the STS program. (See ref. 12.) A fully reusable system like the reference Shuttle II booster-orbiter configuration must place special emphasis on reducing operation costs. This is accomplished, in part, by horizontal vehicle processing and integration, as illustrated in figures 9, 10, and 11. Also, the orbiter and booster are both

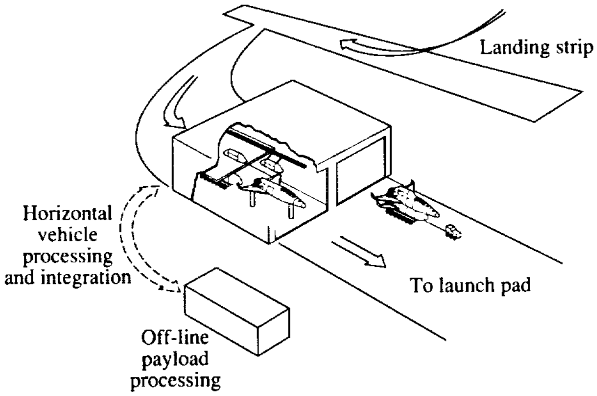

Figure 9. Shuttle II ground processing concept.

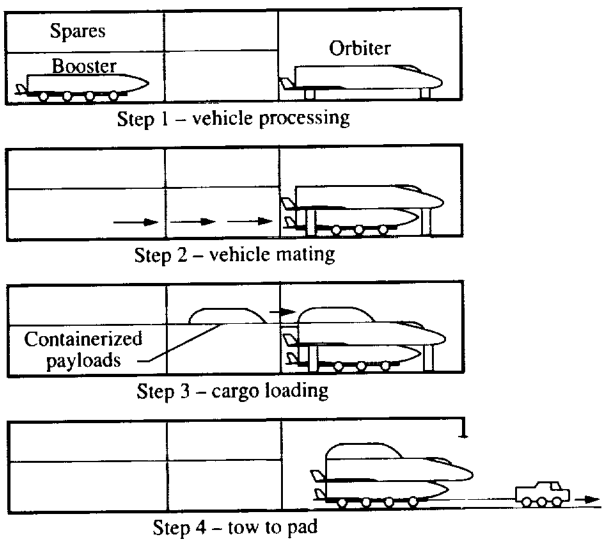

Figure 10. Shuttle II ground assembly procedure concept.

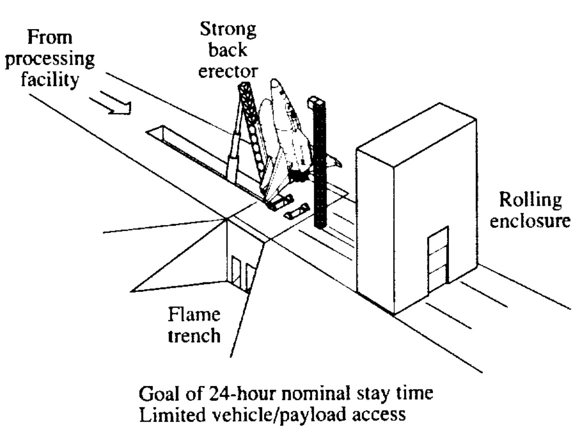

Figure 11. Shuttle II launch procedure concept.

light enough (orbiter dry weight is 159 000 lb, booster dry weight is 108 000 lb) to be air-ferried separately by a Boeing 747 airplane. Instead of hypergolic fuels, which have presented operational difficulties in the Space Shuttle system because of safety requirements, the orbiter uses a common propellant (liquid or gaseous H_2 and O_2) for main engines, OMS (orbital maneuvering system) engines, and RCS (reaction control system) thrusters. It also does not use hydraulic systems or APU's (auxiliary power units); instead, it utilizes all-electric systems: electromechanic actuators, fuel cells, and batteries. Recent advances in fault-tolerant, expert systems and artificial intelligence can also be applied to a Shuttle II vehicle. In addition, the off-line processing of payloads via the payload canister system should contribute to dramatic reductions in operation costs relative to the STS mode of operations. In the design of each of the Shuttle II vehicles, emphasis has been placed on the application of appropriate technologies which improve the operational efficiency of the system.

Booster-Core Vehicle

After designing the booster-orbiter configuration, the first step in creating a system architecture was to take the Shuttle II booster, without any changes, and see if a core vehicle could be designed, with the same set of engines as on the Shuttle II orbiter, to launch 150 000 lb of payload to a 28.5° inclination, 150 nmi circular parking orbit for later transfer to a space station orbit (28.5° inclination, 262 nmi circular). Using the five STME-type engines that were sized for use on the orbiter, the maximum payload that could be achieved was found to be 135 000 lb. However, if an extra engine was added to the core vehicle, keeping the booster unaltered, the desired mission of 150 000 lb of payload was found to be achievable. This booster-core configuration is pictured in figure 12, and some basic characteristics are summarized. A weight statement of the core vehicle is also provided in appendix A, and the APAS aerodynamic characteristics of the core vehicle are contained in appendix D along with the Shuttle II booster and orbiter. In the design of the booster-orbiter, no aerodynamic interference effects caused by the mated configuration were taken into account.

Many of the structural technologies employed on the heavy-lift core vehicle are similar to those of the booster and orbiter. The intertank, skirts, and payload fairing are constructed of organic composites, and the propellant tanks are also aluminum (with no weight penalty for reusability). However, there are some differences in subsystem assumptions. The Shuttle II core vehicle employs APU's and hydraulics, unlike the booster-orbiter vehicle which uses all-electric systems. The core vehicle assumes no technology reduction over the current STS prime power subsystem, unlike the booster-orbiter.

These examples indicate some of the differences in the booster-orbiter vehicle and heavy-lift core vehicle brought about by differences in reusability and technology availability date.

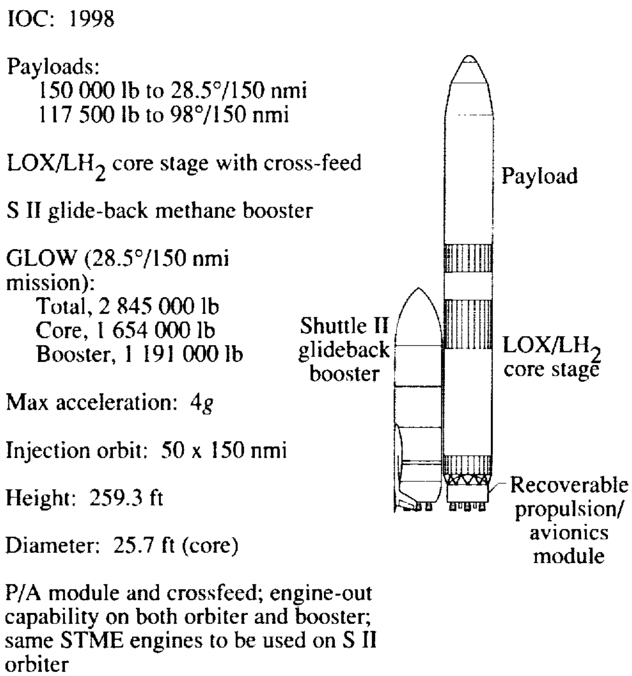

Figure 12. Shuttle II booster-core heavy-lift vehicle.

The booster is staged when it runs out of propellants. This occurs at a Mach number of 2.7 and an altitude of 87 200 ft. As in the booster-orbiter case, it has been demonstrated with POST that the booster can glide back to the launch site from this point. (See ref. 13.) The core length is 260 ft, and the diameter is 26 ft. This diameter is the same as that of the glide-back booster. The tanks are designed to be the same diameter to save the manufacturing costs of retooling the tank fabrication processes. Also included in this configuration is a recoverable P/A module to allow reuse of the costly propulsion system and avionics hardware. The design, development, and testing of this module is an important driving technology for the phased architectural approach.

In a typical mission sequence, the booster-core vehicle is launched from the Eastern Test Range (ETR) at Kennedy Space Center with a GLOW of 2.85M lb and a lift-off T/W of 1.23. It passes through a relatively benign maximum dynamic pressure of 550 lb/ft^2 after 70 sec, and the booster stages after 114 sec. The core vehicle continues on to orbit with a T/W at staging of 1.2. The payload fairing is jettisoned after 192 sec when the dynamic pressure has fallen below 5 lb/ft^2, and the vehicle reaches orbital insertion after 409 sec, with a burnout weight of 290 700 lb.

Core With STAR Vehicle

The payload capability of the core vehicle alone in a single-stage-to-orbit (SSTO) mode, with its six STME-type engines, was found to be 39 800 lb to a 28.5° inclination, 150 nmi circular orbit and 20 300 lb to a 98° inclination, 150 nmi circular orbit. This capability allows the launching of a small STAR vehicle and adapter on top of the core vehicle as shown in figure 13. This STAR vehicle (refs. 12 and 14) could provide an interim manned alternative to the Space Shuttle until a Shuttle II orbiter becomes operational. It would complement the Space Shuttle and Shuttle II booster-orbiter and provide an assured access to space for man after the space station has begun operation. In another version, this craft can function as the crew emergency return vehicle for the space station. The STAR vehicle weighs between 16 000 and 25 000 lb, depending on the configuration, and includes a launch escape system consisting of solid rocket escape motors to provide an 8g escape from a malfunctioning vehicle. (See ref. 15.)

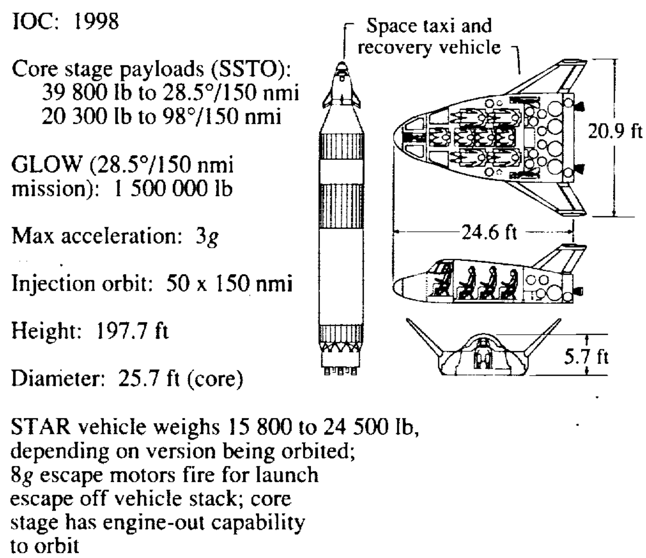

Figure 13. Shuttle II core with STAR vehicle and adapter.

Interim Core With Solid Rocket Boosters

An interim capability to orbit could be achieved in the mid-1990's through augmentation of the core with solid rocket boosters (SRB's) while the liquid-fueled, glide-back booster is under development. An interim heavy-lift vehicle that delivers 100 000 lb of payload to a 28.5° inclination, 150 nmi circular orbit is pictured and described in figure 14. It has no recoverable P/A module or crossfeed provisions; however, the core is sized to accommodate later incorporation of a P/A module and crossfeed components in the manufacturing process. It uses three solid rocket boosters, each of which is a little less than 20 percent of the scale (by mass) of the current Shuttle SRB's. Each SRB is 67 ft long with a diameter of 7 ft. The gross weight of each SRB is 256 500 lb, of which 220 400 lb is propellant used before staging. Each SRB has a burn time of 115 sec, a vacuum thrust level of 511 500 lb, and a vacuum I_{sp} of 267 sec. These characteristics were obtained from average Shuttle SRB characteristics; however, unlike the Shuttle SRB's, each has a constant thrust history and a constant mass-flow rate. To obtain aerodynamic characteristics for the configuration, the core aerodynamics were used, and the reference area was increased to include the SRB cross-sectional area in POST; hence, no aerodynamic interference effects from the mated configuration are taken into account. The vehicle uses six STME-type engines and has a lift-off thrust-to-weight ratio of 1.28. It encounters a maximum dynamic pressure in flight of 830 lb/ft^2, and the payload fairing is jettisoned when the dynamic pressure falls below 5 lb/ft^2.

IOC: 1995

Payloads:
100 000 lb to 28.5°/150 nmi
77 800 lb to 98°/150 nmi

LOX/LH$_2$ core stage
6 STME engines (S II class)

3 solid rocket boosters
(19.8% scale SRB's)

GLOW (28.5°/150 nmi mission):
Total, 2 334 000 lb
Core, 1 565 000 lb
SRB's, 769 000 lb

Max acceleration: 4g

Injection orbit: 50 x 150 nmi

Height: 235.1 ft

Diameter: 25.7 ft (core)

Core stage sized to accommodate later incorporation of P/A module recovery and cross-feed

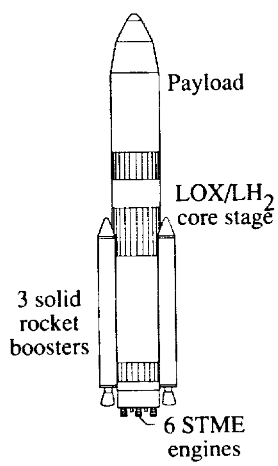

Figure 14. Shuttle II interim core with SRB's.

Trade Studies To Optimize Vehicle Concepts

The main purpose of this paper is to present a series of parametric trade studies to better understand and optimize the vehicles of the Shuttle II reference architecture. To begin, the question of what is meant by the *optimization* of a launch system must be discussed. As noted in the introduction, in this study an optimal launch system is assumed to be the alternative that fulfills the basic mission needs in a safe, reliable manner at the lowest cost. Thus, two questions arise: For a manned system, how much performance and cost should be compromised to assure that the mission is conducted in a safe, reliable manner; and for a preliminary study of future launch systems like Shuttle II, how does one accurately determine and minimize life-cycle costs?

The first question is a very difficult and emotional one, especially in light of the *Challenger* accident. Results from the previously mentioned STAS studies show that life-cycle costs initially tend to decrease as vehicle reliability improves because of fewer payload and vehicle losses; however, as reliability approaches 99 to 100 percent, development and production costs tend to increase rapidly. (See ref. 4.) The question of whether space exploration is worth the risk is ultimately up to investors (or taxpayers) to decide. For the reference, fully reusable Shuttle II system, providing the necessary systems for crew abort and escape decreases the vehicle payload capability by 12 percent, and providing single-engine-out capability from launch to orbit on the booster and orbiter causes an increase in the overall vehicle dry weight of 10 percent. These are significant performance penalties. However, the provision of safety features like engine-out capability can increase vehicle reliability, and, thus, reduce life-cycle costs. Although it was considered beyond the scope of this study, one can quantitatively determine whether the increased reliability provided by a particular system offsets the increase in dry weight or decrease in performance caused by the introduction of that system through computer simulation of vehicle production and operation costs. However, when the possible loss of human life is factored into the cost-benefit analysis, the decisions to include capabilities like engine-out or crew escape become largely qualitative, political ones.

The second question to be addressed is which vehicle design point in a trade yields the minimum life-cycle costs. Proper determination of life-cycle costs for advanced space transportation systems requires careful subsystem analysis to determine design, development, testing, and evaluation (DDT&E) and production costs and requires detailed simulation to determine operation costs for a given flight rate. This process is quite time-consuming and, for a study like Shuttle II, cannot be easily performed for each of the many design points required; thus, for convenience, only certain vehicle parameters that tend to vary relative to costs are considered. It was assumed in this study that development and production costs tend to be direct functions of vehicle dry weight (i.e., the weight of the vehicle without payload, propellant, crew, and residual fluids). Hence the goal in many trades is reduced to minimizing the dry weight of the vehicle and thereby minimizing DDT&E costs. However, a more complex manned vehicle, like the Shuttle II orbiter, will cost more per pound of dry weight than an unmanned system, like the Shuttle II glide-back booster. Also, some subsystems, notably propulsion and avionics, cost an order of magnitude more than simpler subsystems to develop and produce. Thus, more in-depth trade studies would require more detailed analysis than merely minimizing total system dry weight. Furthermore, the equally important role of reducing operation costs which account for over 45 percent of the total recurring costs of the current STS must be considered. For this study, perceived manpower and facility requirements were used to estimate operation costs. For example, one of the trades, discussed in the following sections, involves using a LH_2-fueled glide-back booster with the fully reusable orbiter instead of the reference methane-fueled one. The dry weight of the all LH_2-fueled vehicle is higher; however, the operational ease of working with only one type of fuel and engine, coupled with the savings achieved by eliminating the development of the STBE engine, may more than offset the modest increase in system dry weight. A similar situation is discussed in the staging Mach number trade study, where a system that stages at Mach 3 is chosen over a lighter system that stages at Mach 6 because of the operational efficiency of the Mach 3 staging system.

Reference Booster-Orbiter Configuration

Given the time and computing facilities, a large matrix of booster-orbiter vehicles could be constructed by varying values of lift-off T/W, thrust split, staging Mach number, and other vehicle parameters to minimize total dry weight. In this study, a large matrix of vehicles was not evaluated because most of the trades on major vehicle parameters involve decidedly more complex questions than the simple reduction of total dry weight. Crew escape systems and engine-out capability add dry weight but are desirable to improve safety and reliability. Varying the staging Mach number and the booster fuel involves complex questions of operational efficiency. When questions arise as to how a given change will affect the entire vehicle architecture, the optimization problem becomes even more complex. For this study, each parameter was varied while holding the other major vehicle parameters to constant values to generate parametric curves. For each trade, off-nominal design points were also run as noted to verify that the vehicle design was near optimal.

Thrust Split Trade

In the initial design of a reference vehicle for a study like Shuttle II, reasonable estimates for various vehicle parameters based on previous engineering experience are first assumed. One such parameter is the percentage of total lift-off thrust that is attributed to the booster or the orbiter vehicle. Results from the previous Future Space Transportation Study (FSTS) indicated that a 50/50 thrust split (50 percent of the total lift-off thrust on the booster and 50 percent on the orbiter) yielded an optimal vehicle. (See ref. 16.) For comparison purposes, the entire Shuttle II architecture was designed assuming both a 50/50 thrust split and a 60/40 (60 percent of the thrust on the booster) thrust split on the booster-orbiter vehicle. The results of a thrust split parametric trade study performed on the booster-orbiter configuration with the use of the AVID weights/sizing and POST trajectory programs are presented in figures 15 and 16. These results indicate that the minimum dry weight and gross weight for the booster-orbiter vehicle occurs for the case with a 60/40 thrust split. To concentrate on minimizing dry weight (or up-front costs) is valid for this particular trade because there are no major differences in operations between the vehicles with different thrust splits.

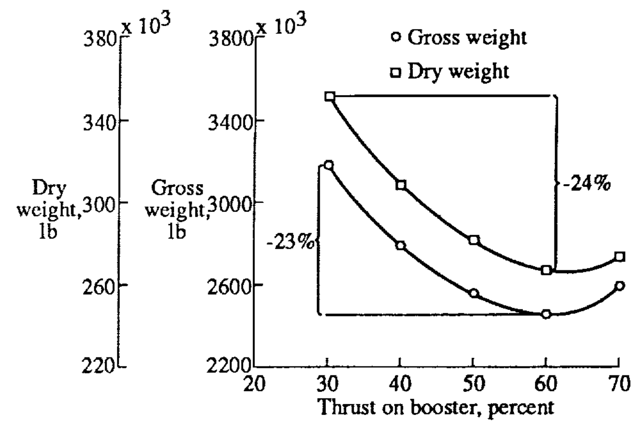

Figure 15. Total dry and gross weights versus thrust on booster for booster-orbiter configuration.

Figure 16 shows that the orbiter achieves minimum dry weight for the 70/30 thrust split case, whereas the booster achieves minimum dry weight at a thrust split of 50/50. The dry weight and gross weights begin to increase rapidly for thrust splits beyond 65 to 70 percent on the booster because of performance losses due to gravity and drag caused by a low orbiter T/W after staging. As the percentage of the total thrust on the orbiter decreases, its T/W at staging rapidly decreases because the orbiter stages full of propellant in each case because of the crossfeed system employed. The orbiter T/W at staging for the 70/30 thrust split case is 0.78 (as compared with 1.0 for the 60/40 case); in fact, no cases were found with thrust splits of less than 30 percent on the orbiter that would allow the orbiter to reach orbit. Hence, even though the dry weight of the more costly orbiter vehicle is slightly less for a 70/30 thrust split, a thrust split of 60/40 was chosen to minimize overall dry weight on the combined system and provide a feasible orbiter T/W value at staging.

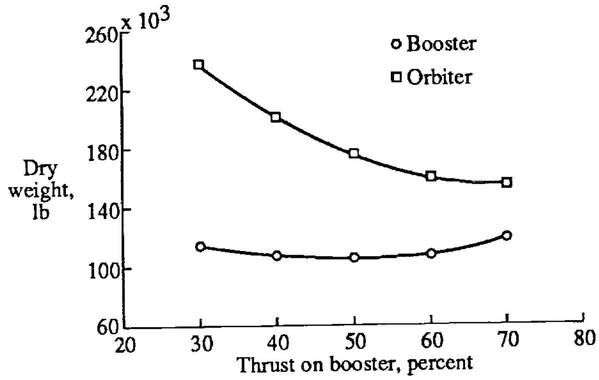

Figure 16. Dry weight of individual booster and orbiter vehicles versus thrust on booster for booster-orbiter configuration.

As a result of this study, the overall booster-orbiter dry weight for the 60/40 thrust split case was found to be 5 percent less than the dry weight for the 50/50 thrust split case. As mentioned earlier, for comparison purposes the entire Shuttle II architecture was designed with both a 50/50 thrust split and a 60/40 thrust split on the booster-orbiter vehicle. For each case, it was assumed that the core vehicle uses six of the same STME-type engines used on the Shuttle II orbiter. The core vehicle from the 60/40 thrust split was found to be 14 percent less in dry weight than the core vehicle from the 50/50 thrust split case. This reduction is mainly due to the 11 000-lb decrease in the propulsion weight of the core vehicle. There is also a 22-percent reduction in the weight of the recoverable P/A module over that of the core from the 50/50 thrust split architecture. It was also determined that the interim core vehicle and the core with STAR configuration are not adversely affected by the use of a 60/40 thrust split on the booster-orbiter vehicle.

Lift-Off Thrust-To-Weight Trade

Throughout the initial design of a reference Shuttle II booster-orbiter vehicle, a value of 1.3 was assumed for the lift-off T/W. This value was judged to be optimal based on the results of previous studies (refs. 16 and 17); however, since such parameters tend to be vehicle dependent, a trade study was performed with a range of T/W and a thrust split of 60/40. The results of this parametric trade are presented in figures 17 and 18. The results shown in figure 17 indicate that the total gross weight is a minimum for a lift-off T/W of 1.4. The minimum dry weight was assumed to occur when T/W is about 1.15. It proved quite difficult to find trajectories for vehicles with T/W less than 1.15 that would achieve orbit; thus, since the dry weight curve in figure 17 is hardly changing at that point, T/W ratios of less than 1.15 were considered to be impractical. It was also found that the minimum nonpropulsion dry weight occurs for a lift-off T/W of 1.3. However, each of these curves is fairly flat in slope, indicating an insensitivity to T/W variations over this range.

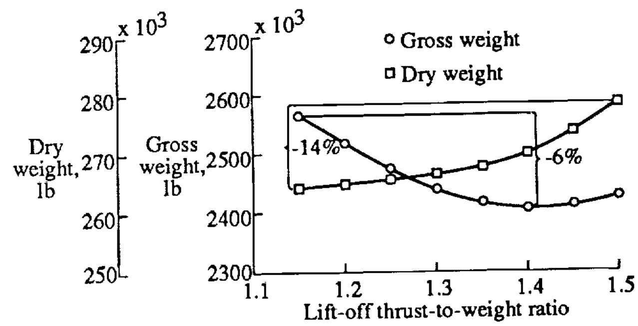

Figure 17. Total dry and gross weights versus lift-off thrust-to-weight ratio for booster-orbiter configuration.

Figure 18 shows that the orbiter dry weight monotonically decreases as the total lift-off T/W is varied from 1.5 to 1.15, whereas the booster dry weight reaches a minimum at a value of T/W of around 1.3 or 1.35. The increase in the booster dry weight as T/W varies from 1.35 to 1.5 is largely because of the added weight of the propulsion subsystem and thrust structure needed to provide these high values of T/W. In fact, as T/W decreases from 1.5 to 1.15, the nonpropulsion dry weight of the orbiter decreases monotonically, whereas the nonpropulsion dry weight of the booster increases monotonically. The total gross weight increases for lower values of T/W because of the additional propellant required to accelerate to orbital velocities.

Once again, for this particular parametric trade, a look at the relative values of total vehicle dry weight is required to determine the optimal vehicle, since there is no reason to expect the recurring costs to be significantly different for the vehicle design points presented. Thus, one might immediately assume that T/W of 1.15 at lift-off should be adopted; however, the effect of the value of booster-orbiter T/W on the entire Shuttle II architecture must be considered because the heavy-lift core vehicle uses the

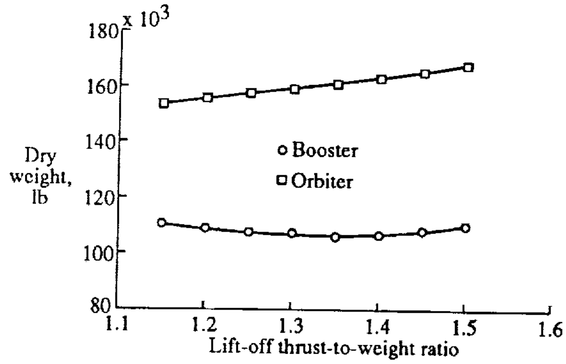

Figure 18. Dry weights of individual booster and orbiter vehicles versus lift-off thrust-to-weight ratio for booster-orbiter configuration.

glide-back booster and six STME-type engines from the booster-orbiter configuration. Repeated design attempts showed that a core vehicle could not satisfy the required mission if the lift-off T/W of the booster-orbiter combination is 1.25 or below. Hence the original estimate of $T/W = 1.3$ on the reference booster-orbiter vehicle was retained because of architectural considerations and to provide a healthy thrust margin despite the dry weight penalty. This dry weight penalty, however, is quite small. The difference in the total vehicle dry weight between vehicles having $T/W = 1.15$ and 1.3 is only 1 percent.

The lift-off T/W parametric trade presented in this section was performed on the reference booster-orbiter with a 60/40 thrust split. Thrust split trades were performed for values of lift-off T/W of 1.25 and 1.35, and in both cases, the 60/40 thrust split proved optimal; hence, no other off-nominal design points were considered.

Staging Mach Number Trade

Staging Mach number is another important design parameter for a two-stage fully reusable next-generation launch system. All the reusable boosters presented by the STAS contractors stage at Mach 6 or above (ref. 4), whereas the reusable booster from the FSTS study stages at Mach 3 (ref. 16). The design-for-operations approach used in the Shuttle II study once again led to the selection of 3 as the staging Mach number. The results of the staging Mach number trade study are given in figures 19, 20, and 21. With the POST trajectory program, previous studies have demonstrated that the Shuttle II booster can glide back, unpowered, from a Mach 3 staging to both the ETR at Kennedy Space Center and the Western Test Range (WTR) at Vandenberg Air Force Base. (See ref. 13.) The WTR case is illustrated in figure 5. If a reusable booster stages at Mach numbers significantly greater than 3, it will require an additional propulsion capability, such as air-breathing engines, to return to the launch site, and it will also require some additional TPS or heat sink because of the increased aerodynamic heating encountered during a return from higher staging Mach numbers. (See ref. 13.) It might be possible to stage at Mach numbers somewhat higher than 3 if the ascent trajectory were modified to allow the booster to glide back; however, only optimal ascent trajectories were considered in this study. Figures 19 and 20 show how the total system dry weight and gross weight vary with staging Mach number, with the additional weight of the air-breathing engines, fuel, and TPS required for each case taken into account. These graphs indicate that, even when the extra engines and TPS are accounted for, both the dry weight and gross weight of the vehicle configuration are minimized at a staging Mach number of about 5.5 or 6.0, similar to results of the STAS studies. Figure 21 shows the individual variances of the orbiter and booster dry weights. A study was also performed to see how the gross and dry weights vary with staging Mach number when no extra TPS or air-breathing engines are added. These results are

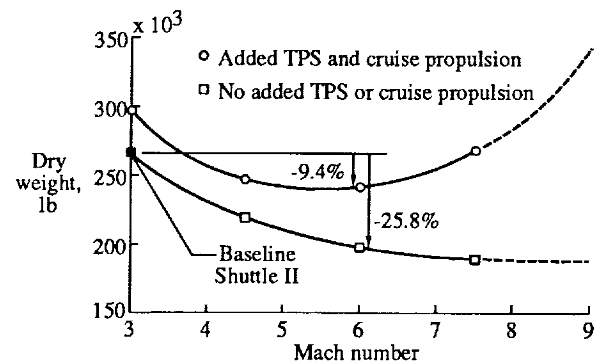

Figure 19. Total dry weight versus staging Mach number for two-stage, fully reusable system with and without extra TPS, air-breathing engines, and fuel.

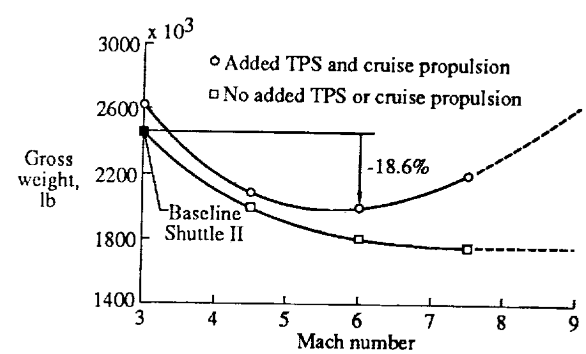

Figure 20. Total gross weight versus staging Mach number for two-stage, fully reusable system with and without extra TPS, air-breathing engines, and fuel.

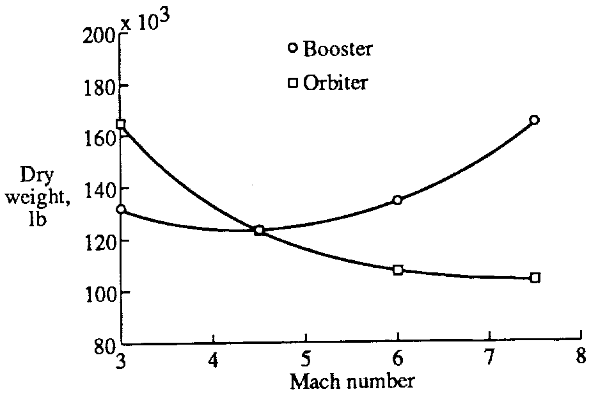

Figure 21. Dry weight of individual booster and orbiter vehicles versus staging Mach number for booster-orbiter configuration with extra TPS, air-breathing engines, and fuel.

also presented in figures 19 and 20. These graphs show that, if the Shuttle II booster-orbiter configuration were to stage at Mach 6 with the necessary TPS and air-breathing propulsion on the booster, instead of staging at Mach 3 where no additional systems are required, a 9-percent savings in dry weight and a 19-percent savings in gross weight could be accomplished.

On the basis of these results, one might immediately assume that a staging Mach number of 6 is obviously desirable. However, there are many other issues to be considered. The main arguments for a Mach 6 staging system are the substantial weight savings mentioned above that will reduce production costs and the ability to have go-around capability upon return to the launch site for landing using air-breathing engines. However, the decrease in operations costs and complexity caused by the elimination of the entire air-breathing system, coupled with the decrease in DDT&E costs and time, could more than offset these advantages if a Mach 3 staging booster is employed. This decrease in DDT&E time also allows for earlier deployment of the booster with the Shuttle II heavy-lift architecture. A Mach 3 staging system should also be more reliable because of the benign heating environment, line-of-sight communication with the booster, and shorter booster return time to the launch site (7 minutes). The elimination of the air-breathing return engines, which could malfunction, should also lead to an increase in vehicle reliability.

One final issue to be considered is the size match between the orbiter and the payload canister. From figure 21 we see that the orbiter continues to decrease in weight as the staging Mach number increases. Accompanying this decrease in weight is a corresponding decrease in vehicle length. The reference Shuttle II orbiter pictured in figure 2 has a length of 141 ft, whereas the corresponding Mach 6 staging orbiter has a length of only 112 ft. Hence, additional dry weight would most likely have to be added to configure the Mach 6 staging orbiter to properly accommodate the required payload volume and to assure that aerodynamic performance is not compromised substantially. After consideration of all the issues involved, a Mach 3 staging system was adopted for the reference Shuttle II booster-orbiter configuration; however, a more detailed quantitative study of the operational complexity of a Mach 6 staging system would be required to properly evaluate these results.

Crossfeed Trade

Both the Shuttle II booster-orbiter and booster-core configurations employ a crossfeed system, whereby propellant is drawn from the booster propellant tanks and fed directly to the orbiter or core main engines to allow the orbiter to be full of propellant at staging. Figure 22 illustrates the weight savings afforded by the utilization of such a system on the Mach 3 staging booster-orbiter vehicle. For a system without crossfeed capability, the gross weight would be 62 percent higher and the dry weight 51 percent higher. With this system, the booster and orbiter are sized so that the booster propellants are depleted when the vehicle reaches Mach 3. At this point the booster glides back to the launch site, and the orbiter, full of propellant, continues to orbit with the payload. The added cost and complexity of such a system was judged to be minimal when compared with the large dry and gross weight savings on the vehicles, especially since there is an experience base with the crossfeeding of propellants (LOX/LH_2) from the Space Shuttle external tank to the orbiter.

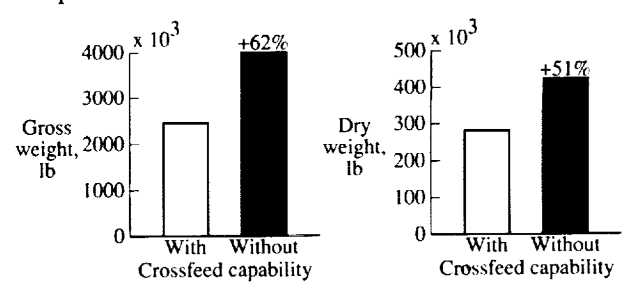

Figure 22. Reference booster-orbiter weights with and without crossfeed capability.

Engine-Out Capability Trade

All the vehicles in the Shuttle II reference architecture shown in figure 1 have engine-out capability from launch to orbit. Thus, both a booster engine (STBE) and a main engine (STME) could malfunction any time from lift-off until orbital insertion, be shut down, and the vehicle could still complete its mission. The STBE-type engine used on the booster can be throttled from 85 to 100 percent of its total power, whereas the throttling range of the STME-type engine used on the orbiter and core is 80 to 100 percent. To provide engine-out capability on the booster, six STBE-type engines are utilized at 85 percent of their thrust capacity; hence, if an engine fails, the remaining five engines are throttled to their full 100-percent thrust levels to assure no loss in capability. Similarly on the orbiter, five STME-type engines are utilized at 80 percent of their thrust capacity; thus again, if an engine fails, the remaining four engines are throttled to their full 100-percent thrust levels. This capability cannot be achieved, however, without significant sacrifices in vehicle performance. As illustrated in figure 23, performance trades indicate that the addition of engine-out capability to the booster-orbiter configuration causes an 11-percent increase in dry weight and a 7-percent increase in gross weight. Thus, production (up-front) costs would be significantly increased by the inclusion of engine-out capability on the reference vehicle. However, operations (recurring) costs would be reduced because the STBE and STME engines are not constantly operating at their full potential and hence could last for more flights when refurbished and because of the reduced number of failures of the launch system. It was concluded that the increased reliability and, most importantly for a manned system, the enhanced safety provided by engine-out capability from launch to orbit are probably worth the penalties paid in vehicle performance and production costs.

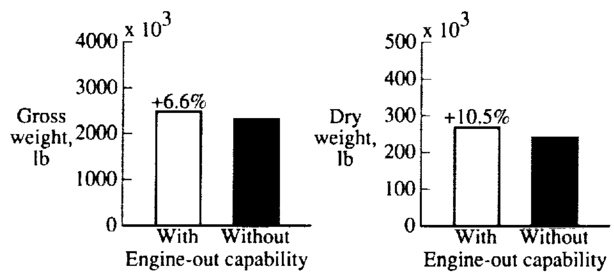

Figure 23. Reference booster-orbiter weights with and without single engine-out capability from launch to orbit.

Payload Parametric Sizing

The reference Shuttle II mission was chosen to be the launch and return of 12 000 lb of payload to polar orbit (98° inclination, 150 nmi circular). The resulting system yielded a payload of 37 000 lb to a space station orbit (28.5° inclination, 262 nmi circular). Although this particular mission was arrived at through examination of future launch needs, a reusable booster-orbiter vehicle can be designed for other payloads and missions with the same tools and methods. The results of such a parametric trade are presented in figure 24. The variations of dry and gross weight are presented for polar missions with payloads ranging in weight from 0 to 36 000 lb. For each of these different payload weights, the payload shroud size and weight were assumed to remain unchanged. The results in figure 24 show that the variations of vehicle dry and gross weights with payload are essentially linear. The slope of these linear variations indicates that if 1 lb of payload is added to the vehicle, its total dry weight would increase by about 3.4 lb. Of this total, 2 lb of the increase is in the orbiter total, and 1.4 lb of the increase is attributed to the booster. Hence, the payload sensitivity of the booster-orbiter configuration can readily be seen.

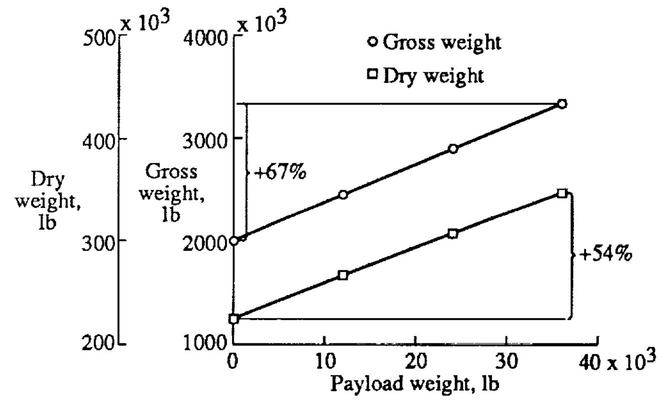

Figure 24. Total booster-orbiter dry and gross weights versus payload weight to polar orbit (98° inclination, 150 nmi).

Payload Variation With Orbit Inclination Angle

Although the Shuttle II booster and orbiter are designed to carry 12 000 lb of payload to a 98° inclination, 150 nmi circular orbit, the amount of payload that can be transported to 150 nmi circular orbits with other inclinations using the booster-orbiter configuration is also of interest. Depending on the mission, the reference booster-orbiter vehicle utilizes two different launch sites because of launch azimuth constraints. For missions to low-inclination orbits, including the space station, the booster-orbiter vehicle would be launched from ETR at Kennedy Space Center. For missions to high-inclination orbits, like the baseline mission, the booster-orbiter vehicle would be launched from WTR at Vandenberg Air Force Base. This additional facility is needed because polar launches from ETR would have to occur over land or require expensive orbital plane changes, neither of which is desirable. Payload variations with orbit inclination angle are presented in figures 25 and 26 for launches of the booster-orbiter vehicle from both ETR and WTR. These curves show that, as the inclination angle decreases, the payload capability increases. This is because lower inclination angles allow the vehicle to utilize a larger component of the Earth's rotational velocity to give it a sizable initial inertial velocity. Note that the value shown for the payload capability from ETR to a 28.5° inclination orbit is quoted as 44 000 lb. This payload figure is for a 150 nmi circular target orbit. To reach the space station orbit (28.5, inclination, 262 nmi circular), an additional 7000 lb of OMS propellant is needed. Thus the payload weight that the booster-orbiter can take to the space station is actually 37 000 lb.

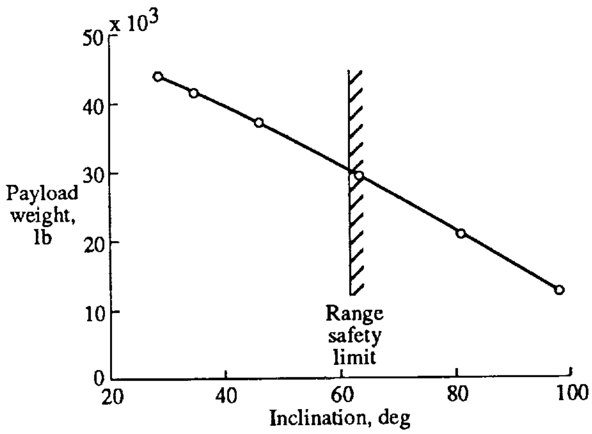

Figure 25. Payload weight capability of reference booster-orbiter vehicle versus orbit inclination angle (150 nmi orbit) for launch from ETR.

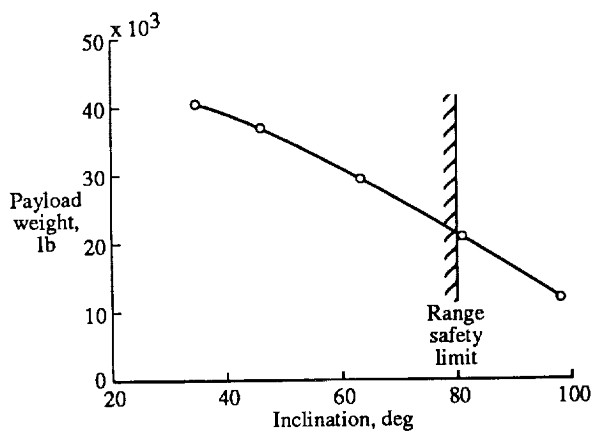

Figure 26. Payload weight capability of reference booster-orbiter vehicle versus orbit inclination angle (150 nmi orbit) for launch from WTR.

Technology Level Trade

In the conceptual design of a future space transportation system like Shuttle II, assumptions must be made as to what structural and subsystem technologies will be available when the development actually begins. For a development cycle to begin in 1992, technologies were selected that were expected to be available through normal growth progression from STS technologies. Any major technological improvements after that time would probably occur too late to be incorporated on the vehicles. The primary structural technology assumptions for the Shuttle II booster and orbiter are illustrated in figures 7 and 8.

In the AVID weights/sizing program, the structural weights and the weights of subsystems and their components are modeled as equations. The equations are obtained from historical mass relations (as discussed previously), material densities, or similar STS subsystems. The equations used for each of the vehicles in the reference Shuttle II architecture are provided in appendix B. Each of these equations gives weights based on STS technology. Each is then multiplied by an appropriate weight reduction factor to indicate the weight savings that can be accomplished in that subsystem or component if evolutionary technology improvement to the year 1992 is assumed. These weight reduction factors vary in value from equation to equation, and some subsystems remain unchanged. In the technology level trade presented in figure 27, however, these constants were set to the same value. Across-the-board reductions in dry weight of 0, 20, 40, and 60 percent over current STS technology were assumed. If the reference booster-orbiter dry weight were plotted in figure 27, the 1992 technology level assumed in the Shuttle II study would be approximately equivalent to a 25-percent across-the-board weight reduction over STS technology, as shown in figure 28.

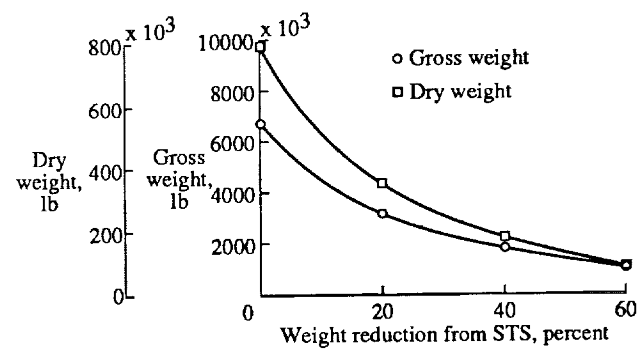

Figure 27. Total dry and gross weights versus weight reduction over STS technology for reference booster-orbiter vehicle.

The effect of technology assumptions on a SSTO system is also of interest. A SSTO system would offer significant reductions in operation costs. (See ref. 18.) With the same type of weight analysis as used for the SSTO vehicle, we see in figure 28 how the two-stage fully reusable Shuttle II and SSTO systems compare for different technology levels. For the purposes of this study, the SSTO vehicle was assumed to have the same geometry and mission as the Shuttle II orbiter. The engine performance characteristics are also the same as the Shuttle II orbiter, and the lift-off T/W was assumed to be 1.3. At STS levels, a SSTO vehicle could not be built. For Shuttle II technology levels, a SSTO vehicle could perhaps be built but would probably be too large to be cost-effective. However, for technology levels assuming 30- to 40-percent reductions over STS levels, the SSTO vehicle becomes competitive and at even higher levels would be more desirable than a two-stage system. The advanced technology range in figure 28 is approximately that which the National Aero-Space Plane (NASP) studies (ref. 19) are examining in detail for future horizontal-takeoff, air-breathing systems.

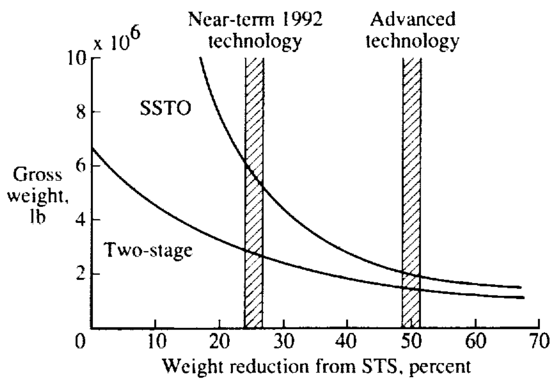

Figure 28. Total gross weight of two-stage and SSTO Shuttle II vehicles versus weight reduction over STS technology.

Trades on Booster-Core Vehicle

Payload Parametric Sizing

The reference design mission for the booster-core heavy-lift vehicle described earlier (fig. 12) was chosen to be the delivery of a 150 000-lb payload to a 28.5° inclination, 150 nmi circular orbit by the late-1990's. This choice was driven mainly by Department of Defense (DOD) needs, assuming some level of Strategic Defense Initiative (SDI) experimentation or deployment; however, this capability would also allow for civil construction of large space structures, deployment of large geosynchronous platforms, and launch of material or fuel for lunar or Mars missions. (See ref. 4.) An expendable core vehicle (with a recoverable P/A module) to be used with the reference Shuttle II booster that utilized the exact same set of five (STME-type) engines as the orbiter was found to have a payload capability of 135 000 lb if engine-out capability is maintained. By adding an extra STME-type engine, the vehicle payload capability was increased to the desired 150 000 lb. A weight statement for this reference core is given in appendix A. For this case, the booster no longer stages at Mach 3. It stages when its propellant is depleted, which occurs at Mach 2.7.

The effect of payload size on vehicle weight is presented in figure 29 for the heavy-lift core vehicle with six STME-type engines, each with a vacuum thrust level of 311 500 lb. For each case, the size of the payload fairing is determined by assuming a payload density of 4 lb/ft^3. The reference booster-core vehicle, which carries 150 000 lb, is on a very high-growth portion of the curves in figure 29; hence, for payloads in excess of 150 000 lb, another engine would be required to improve the T/W value at staging. The booster used with the core vehicle was not designed to stage at Mach greater than 3; thus, for payloads of 145 000 lb or less, the thrust level of the extra STME engine must be limited during the boost phase. Derating the extra engine in this manner was found to be more efficient than off-loading propellant from the booster.

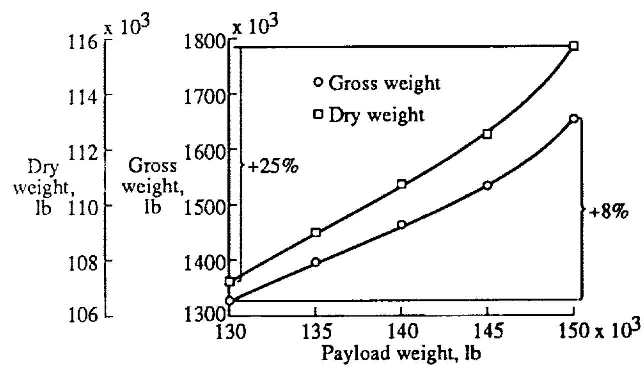

Figure 29. Dry and gross weights of heavy-lift core vehicle versus payload weight to space station transfer orbit (28.5° inclination; 150 nmi).

Optimal Booster-Core Vehicle

The approach taken in the design of the Shuttle II architecture was to optimize the glide-back booster for use with the Shuttle II orbiter. Then, a heavy-lift core vehicle was designed for use with this same booster. This approach is desirable because the booster-orbiter manned configuration is by far the more costly vehicle. Hence, this system should be optimized with respect to life-cycle costs, and the heavy-lift booster-core system would likely not be optimum.

However, it is instructive to see the effect on the heavy-lift system if the booster is designed to optimally fulfill the booster-core reference mission alone. The resulting booster-core vehicle would also be similar to those being studied under the joint NASA/DOD Advanced Launch System (ALS) Program to provide a heavy-lift launch capability by the late-1990's using evolutionary components. (See ref. 20.) This new booster-core vehicle was assumed to have a staging Mach number of 3, a lift-off T/W of 1.3, and equal booster and core stage diameters of 26.4 ft for manufacturing efficiency. As in the design of the booster-orbiter (fig. 17), a T/W of 1.3 is chosen as a compromise between minimizing overall dry and gross weight. For this case, decreased gross weight resulted in decreased core stack height, which could simplify operations. A thrust split trade between the booster and core was performed (fig. 30), and once again a thrust split 60/40 proved to be optimal for a lift-off T/W of 1.3.

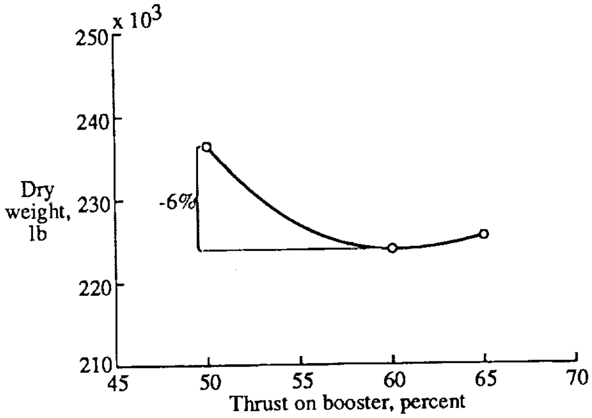

Figure 30. Total booster-core vehicle dry weight versus thrust on booster for booster-core configuration with optimal booster.

From these results, the penalty incurred by the use of a nonoptimal booster on the Shuttle II heavy-lift system can be seen. An optimal booster-core system requires a larger booster than the Shuttle II reference to stage at Mach 3. The reference booster is 9 percent less in dry weight, whereas the core vehicle from the reference Shuttle II architecture is 9.3 percent higher in dry weight and 13 percent higher in gross weight than the vehicles from the optimal booster-core configuration. It should also be noted that the use of the Shuttle II reference booster leads to a core vehicle with a stack height of 259 ft, whereas the stack height for the more optimal booster-core is 234 ft. Thus the effect of using the non-optimal, Shuttle II reference booster for a future heavy-lift launch system is not terribly adverse. The total dry weights of the two systems are about the same, but there is a fairly small (3 percent) penalty paid in the total system gross weight because of the large gross weight reduction in the core vehicle. Also, the core vehicle from the optimal booster-core configuration actually takes up slightly less payload (30 200 lb to space station orbit) in the single-stage-to-orbit mode used to launch the STAR vehicle than the reference core vehicle. However, this payload capability is still within the range of acceptability for the STAR vehicle weights. After examining all these considerations, it was concluded that the benefits obtained by sharing a common booster between the orbiter and heavy-lift core vehicle more than offset the penalties paid for not having an optimal booster when incorporating a future heavy-lift system into a vehicle architecture like the one presented in the Shuttle II study.

All LOX/LH_2 Propellant System

All the vehicles presented thus far in the reference Shuttle II architecture use methane-fueled booster engines and liquid-hydrogen-fueled main engines. These engine choices are a direct result of the STBE and STME future engine studies conducted by contractors and monitored by the Marshall Space Flight Center. (See refs. 10 and 11.) The three contractors conducting the studies concluded that the best hydrocarbon fuel for an advanced space transportation booster engine to be flown in the late-1990's is methane, with a small hydrogen gas-generator cycle. Methane was cited as a clean-burning fuel, without the combustion instability problems associated with RP-type fuels. Liquid hydrogen was chosen as the proper fuel for advanced space transportation main engines. These STBE and STME engines were chosen as guidelines for the Shuttle II booster and main engines.

Methane was adopted as the Shuttle II booster fuel as a result of the trades performed in the STBE study. However, the important question remains of what sort of penalty would be incurred by the use of liquid-hydrogen-fueled orbiter engines *and* booster engines. Different fuels have different densities, different specific impulses, and lead to engines with different T/W values. Each of these factors should be properly traded off against the others to get a complete picture of the effect of choosing one fuel over another. The higher I_{sp} of LH_2 must be traded off against the higher density of methane. Thus, a booster and orbiter have been designed to fulfill the reference Shuttle II mission that use STME-type engines on both the orbiter and booster. This system also stages at Mach 3, and propellant is also cross-fed to the orbiter. The results of this fuel trade are presented in figure 31, which indicates that the gross lift-off weight is actually 3.8 percent less for the all LOX/LH_2 vehicle, and the dry weight increases by only 3.0 percent. This increase in dry weight would cause a small increase in production costs; however, if an all LOX/LH_2 vehicle were chosen for a future space transportation system, the entire development program for the STBE engine could be eliminated. In addition, the use of only a single fuel would reduce vehicle operations costs by eliminating hydrocarbon fuel storage and handling facilities and refurbishment facilities for an extra type of engine. Engine production costs could also be reduced since a larger number of the same engine would be produced.

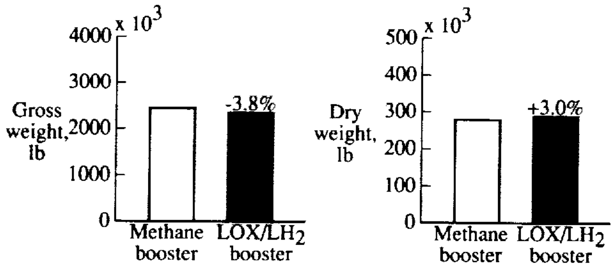

Figure 31. Total gross and dry weights of Shuttle II booster-orbiter configuration with reference methane-fueled booster and liquid-hydrogen-fueled booster.

Similar results were recently obtained in independent studies in reference 21. This study used all STME engines on a two-stage, 30 000-lb-payload (28.5° inclination) booster-orbiter configuration and found a dry weight increase of around 2 percent and a small decrease in gross weight. This suggests that the STBE engine may not be cost-effective to develop. This result is in contrast to some previous future system studies. For example, a vehicle alternative with a LH_2-fueled booster considered in reference 17 was 10 percent higher in dry weight than its hydrocarbon-fueled counterpart. The same RP-1 engines used in the earlier FSTS vehicle study (ref. 16) were incorporated on the Shuttle II booster-orbiter vehicle, and the system with the LH_2-fueled booster was found to be 8 percent higher in total dry weight. The present results and those from reference 21 show much smaller percent differences because the results are based on the use of very different hydrocarbon engines. Many previous studies have used propane and RP-1 as booster fuels. These fuels are more dense than the methane chosen for use in the STBE studies. Most importantly, however, booster engines used in previous studies also had much more optimistic thrust-to-weight ratios. Hence, if the methane-fueled engines presented in the STBE study are truly the best reusable hydrocarbon engines that will be available in the late-1990's, serious consideration should be given to using liquid hydrogen as the primary liquid booster fuel for the next generation of launch vehicles.

Booster-Orbiter Vehicle

Because of the results of the booster fuel trade study, the all LH_2-fueled system must be considered as an attractive alternative to the reference Shuttle II system presented previously. Hence the same type of trades on major vehicle parameters were conducted to determine the optimal LH_2-fueled booster-orbiter configuration to perform the reference Shuttle II mission.

Thrust split trade. For the all LH_2-fueled vehicle, the STME-type engines used on both the booster and orbiter should be of the same size to reduce costs. Also, at least five STME-type engines are required on each vehicle to assure engine-out capability from launch to orbit. Hence, the thrust split trade study presented in figures 32 and 33 was performed by varying the number of engines of equal thrust levels on the booster vehicle rather than using simple percentages. Cases were run for five STME-type engines of the thrust level shown in table 1 on the orbiter and five, six, seven, eight, and nine of the same STME-type engines on the glide-back booster. As shown in figure 32, the lowest vehicle dry weights occur for the cases of seven or eight engines on the booster. Both cases are essentially equal; hence, the case with five engines on the orbiter and seven engines on the booster was chosen to be the reference to minimize operational complexity. This is the case that provides the 3.8-percent gross weight reduction and 3.0-percent dry weight increase over the reference booster-orbiter vehicle which has a methane-fueled booster. The trends demonstrated in figures 32 and 33 are very similar to those discussed earlier in figures 15 and 16. Once again, this thrust split trade was performed for a booster-orbiter configuration with a lift-off T/W of 1.3.

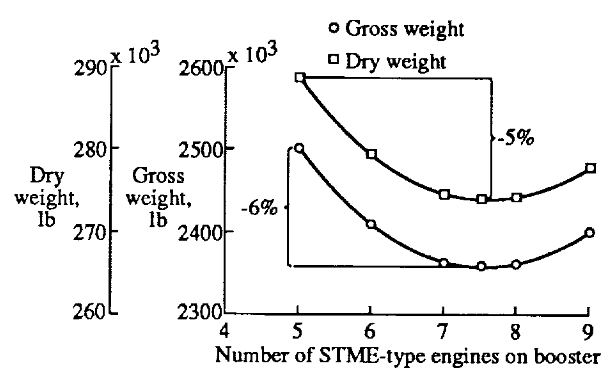

Figure 32. Total dry and gross weights versus number of STME-type engines on booster for liquid-hydrogen-fueled booster-orbiter configuration (with five STME-type engines on orbiter).

Thrust-to-weight trade. For the all LOX/LH_2 vehicle with seven engines on the booster and five engines on the orbiter, the effect of changes in the lift-off T/W on the total vehicle dry and gross weights was examined. Vehicles were sized for lift-off T/W values of 1.25, 1.3, and 1.35. These vehicles show the same sort of variations that led to the choosing of a T/W of 1.3 for the methane booster and hydrogen orbiter. The gross weight decreases for values of lift-off T/W greater than 1.3, and the dry weight continues to decrease slightly for T/W values of less than 1.3. Both these curves are relatively flat in slope: the total dry weight changes by less than 0.5 percent over the T/W range of 1.25 to 1.35, and over the same range, the gross weight changes by only 1.5 percent. These results suggest that a lift-off T/W of 1.3 should again be chosen for the booster-orbiter configuration with LH_2-fueled booster. Results to be discussed later will show that a lift-off T/W of 1.3 leads to a feasible LH_2-fueled booster-core configuration when a heavy-lift vehicle architecture is designed with the same LH_2-fueled booster from the booster-orbiter configuration.

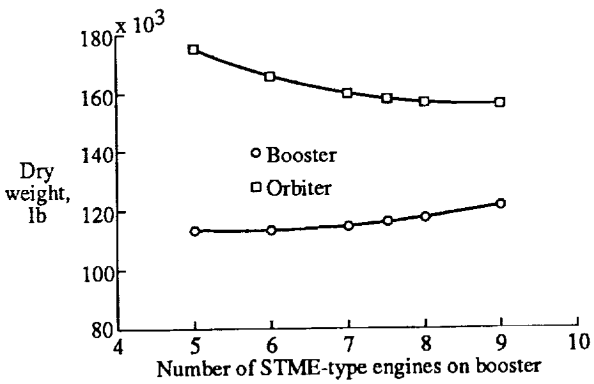

Figure 33. Dry weight of individual booster and orbiter vehicles versus number of STME-type engines on liquid-hydrogen-fueled booster-orbiter configuration (with five STME-type engines on orbiter).

Other parametric trades. As a preliminary investigation into a staging Mach number trade, a booster-orbiter vehicle with a LH_2-fueled booster was designed to stage at Mach 6. Extra TPS and air-breathing engines with fuel were added to the booster in appropriate amounts. The dry weight of the vehicle that stages at Mach 6 is 4.5 percent less than its Mach 3 counterpart, and the gross weight is 14 percent less than the Mach 3 vehicle. This difference is significantly less than the potential weight savings seen earlier for the methane-fueled booster-orbiter that stages at Mach 6. For the reference fully reusable system with methane-fueled booster, the total dry weight of the vehicle that stages at Mach 6 was 9.4 percent less than the Mach 3 case, and the total gross weight was 18.6 percent less than its Mach 3 counterpart. This indicates that staging at Mach 3 because of operational considerations might be even more desirable for an all LOX/LH_2 two-stage system.

To see the effect of varying the technology level of the LH_2-fueled system, a booster-orbiter vehicle was redesigned assuming a 0-percent reduction over present STS technology. The previous all LOX/LH_2 booster-orbiter assumed (like the reference Shuttle II) 25-percent reductions over STS technology. This portion of the study showed that the 1992-technology (25-percent reduction), LH_2-fueled booster-orbiter vehicle provided a dry weight reduction of 71 percent over a similar vehicle designed with STS technology levels. For the methane-fueled system shown earlier, this reduction was 63 percent. Hence, the all LOX/LH_2 system does not compare nearly as well with the baseline methane-fueled system at lower technology levels because the decrease in propellant bulk density leads to a significant increase in vehicle structural weight. This may provide yet another reason why systems using liquid hydrogen as a primary booster fuel have not fared well in past studies.

All LH_2-Fueled Booster-Core Vehicle

To investigate properly the desirability of using a LH_2-fueled booster for a future space transportation system like the reference Shuttle II architecture, the effect on the entire vehicle architecture must be considered. To examine this effect, a heavy-lift core vehicle was designed to take 150 000 lb to a 28.5° inclination, 150 nmi circular orbit in the same manner as the previous methane-fueled booster case. The booster with seven STME-type engines from the booster-orbiter configuration was used unchanged, and a core vehicle was designed using six of these same STME-type engines for propulsion. The heavy-lift core vehicle designed in this manner actually is 0.5 percent less in dry weight and 2 percent less in gross weight than the core designed for use with the Shuttle II methane-fueled booster. For the complete all LH_2-fueled booster-core configuration, the total dry weight (including booster) is 2.9 percent higher than the booster-core configuration with methane booster, and the total gross weight is 4.5 percent less.

The methane-fueled booster from the reference Shuttle II booster-core configuration is staged when it runs out of propellant, and the core stage continues on to orbit. This occurs at a Mach number of 2.7. For the all LOX/LH_2 heavy-lift vehicle, since the booster and core share common propellants, the booster can continue on to higher velocities and stage at Mach 3. At some point in the trajectory, the booster stops crossfeeding propellant to the core vehicle in order to conserve enough propellant for itself to continue on to Mach 3. At the point where the crossfeeding is terminated, the core stage engines begin drawing propellant from the core vehicle propellant tanks. Thus, both the core and booster engines continue to burn in parallel from launch to Mach 3. This additional performance allows the core vehicle from the LH_2 booster case to actually have a lower dry weight than the one from the reference Shuttle II architecture.

Concluding Remarks

Conceptual and preliminary launch vehicle design is a complex, iterative process. The design of the best future launch system to meet a set of given mission requirements is basically a multivariate optimization problem, albeit not a very straightforward one. The optimization problem is complicated by the need to balance performance and operational considerations to achieve a safe, reliable vehicle with the lowest possible life-cycle costs. In the preliminary design of a future launch system, like the Shuttle II architecture, values must be chosen for various vehicle parameters (i.e., lift-off thrust-to-weight ratio (T/W), thrust split percentage, staging Mach number), and choices must be made concerning major vehicle systems (i.e., type of propellants, type of engines, safety features). The designer must understand the effects on the entire system of varying these parameters and subsystems. Hence, the results of parametric trades, using state-of-the-art trajectory and weights/sizing programs, provide the designer with important insights into the optimization of future launch vehicles and associated architectures.

This paper has summarized a variety of reference Shuttle II vehicle concepts. A fully reusable vehicle concept has been examined as a next-generation, manned space transportation system. A heavy-lift expendable core vehicle has also been defined that shares a common booster with the fully reusable Shuttle II vehicle in an architectural approach. A series of trade studies has been conducted to optimize the reference Shuttle II architecture. In each trade discussed, special attention has been given to the major vehicle performance and operational issues involved.

Another important result of the present Shuttle II study is the investigation of an architectural approach to an advanced space transportation system. The phased-approach architecture presented in this paper provides a logical growth path and timetable for the development of such an architecture. The civil and Department of Defense future space launch requirements indicate that, at some point in the near future, the United States will need a heavy-lift launch system and a next-generation manned system. If both these systems share a common booster, common engine type, common operating and launch facilities, and some common subsystems and technologies, large cost savings could be realized. The results of the present study suggest that an architectural approach that provides for assured manned access to space should be given serious consideration for a next-generation space transportation system.

The common thread running throughout the features of each of the candidate Shuttle II vehicles and the parametric trade studies results is a design-for-operations approach. Many previous launch systems, including the current space transportation system (STS), have been driven by a desire to maximize vehicle performance, usually at the expense of future operational considerations, because of budgets being fixed or reduced. For a next-generation launch system to truly achieve reliable, safe, low-cost, and routine access to space, vehicle operational considerations must be given major emphasis from the outset of the design process. Hence, in every major parametric trade, the desire to maximize performance and minimize up-front costs by minimizing vehicle dry weight must be sufficiently tempered by the goal of reducing recurring costs and turnaround time by simplifying vehicle operational procedures. Although many of the assumed technological advances contribute to significant weight savings in each of the Shuttle II vehicles discussed, a portion of that weight savings has been applied to aspects of the vehicle design that enhance the operations, reliability, and safety factors of the system. The trade studies presented herein give evidence of these performance sacrifices on the booster-orbiter configuration: staging at Mach 3 increases vehicle dry weight by 9.4 percent over staging at Mach 6, providing single-engine-out capability from launch to orbit increases dry weight by 10.5 percent, using a LH_2-fueled booster would increase total dry weight by 3.0 percent, and providing systems for crew escape decreases the vehicle payload capability by almost 12 percent. These are dramatic performance sacrifices; however in each case, the performance considerations are judged to be outweighed by reliability, safety, and operational considerations.

The results of the trade studies performed on the vehicles of a reference Shuttle II mixed fleet have provided an increased understanding of the relative importance of each of the major vehicle parameters and, hence, should contribute to the selection of the system which will fulfill the given mission for the lowest life-cycle cost. As a result of trades on the reference booster-orbiter configuration with a methane booster, the study showed that 60 percent of the total lift-off thrust should be on the booster and 40 percent on the orbiter. This led to a 5-percent dry weight savings on the booster-orbiter and a 14-percent dry weight savings on the associated heavy-lift core vehicle over a vehicle with a thrust split of 50 percent on the booster and 50 percent on the orbiter. Also, the lift-off T/W on the booster-orbiter should be 1.3. This leads to a low dry weight and still provides enough thrust to allow the design of a heavy-lift architecture. As the result of another trade study, the dry weight of the reference booster-orbiter was found to be a minimum for a staging Mach number between 5.5 and 6; however, a staging Mach number of 3 was chosen for a variety of operational considerations. Other trade studies on the booster-orbiter vehicle demonstrate that the crossfeeding of propellant during boost phase is desirable, and engine-out capability from launch to orbit was judged to be worth the performance penalty. Technology assumptions made during the design of the Shuttle II vehicles were shown to be approximately equivalent to a 25-percent across-the-board weight reduction over STS technology. The booster-orbiter vehicle was also sized for a wide variety of payloads and missions to different orbits. The heavy-lift core vehicle was also sized for different payload weights in case a 150 000-lb mission proves unneeded. An optimal booster-core system was designed and found to be only 3 percent less in gross weight and almost equal in dry weight; hence, a large performance sacrifice is not made to include a heavy-lift system in a vehicle architecture, sharing a booster with a manned orbiter.

Many of these same parametric trades were also performed on the all LH_2-fueled fully reusable concepts. If a booster-orbiter vehicle is designed with liquid-hydrogen main engines on both the booster and orbiter, the total vehicle dry weight is only 3.0 percent higher than the reference booster-orbiter, and the gross weight is 3.8 percent less. For this booster-orbiter vehicle, a lift-off T/W of 1.3, a thrust split of about 60 percent on the booster, and a staging Mach number of 3 all proved to be desirable. The associated heavy-lift core vehicle, designed for use with the LH_2-fueled booster, is 0.5 percent less in dry weight and 2 percent less in gross weight than the reference heavy-lift core vehicle. This modest dry weight increase for a LOX/LH_2 Shuttle II system should be more than offset by the elimination of the entire methane booster engine development program and the savings in operation costs realized by the elimination of an entire fuel type.

NASA Langley Research Center
Hampton, VA 23665-5225
January 4, 1991

Appendix A

Shuttle II Vehicle Weight Statements

Appendix A contains the AVID weights and geometry statements for the reference Shuttle II orbiter, booster, and core vehicles. These final statements are the result of many iterations between the POST trajectory program and the AVID weights and sizing program as described in the section "Design Methods."

Shuttle II
Two-Stage Fully Reusable Vehicle

Orbiter weights—LOX/LH_2

Group number	Group	Weight, lb		
		Subgroup		Group
1.0	Wing			14 919
	Exposed wing		10 840	
	Carry-through		4 079	
2.0	Tail			726
3.0	Body			54 152
	LOX tank		10 736	
	LH_2 tank + insulation		18 411	
	CH_4 tank		0	
	Basic structure		8 281	
	Nose section	4 586		
	Aft section	2 616		
	Access tunnel	339		
	Tunnel fairing	740		
	Thrust structure		2 220	
	Crew cabin		4 881	
	Body flap		442	
	Intertank 1		5 393	
	Intertank 2		3 788	
4.0	Thermal protection system			20 093
4.5	Helium purge system			1 919
5.0	Landing gear/separation system			6 536
	Landing gear		5 909	
	Separation		627	
6.0	Propulsion			29 736
	Powerheads		17 647	
	Nozzles		2 486	
	Pressurization & feed		7 129	
	Gimbals		1 775	
	Crossfeed		699	
7.0	Propulsion, RCS			2 879
8.0	Propulsion, OMS			1 333
	Engines		287	
	Feed lines		706	
	Pressurization		340	
9.0	Prime power			3 087
	Fuel cells		1 195	
	Reactant dewers		698	
	Batteries (surface controls)		597	
	Batteries (gimbals)		597	
10.0	Elec conversion & distribution			4 292
	Power conversion		772	
	Avionics cabling		1 848	
	Elec surface control cabling		1 672	
11.0	Hydraulics			0

12.0	Electric actuators		1 711
	Elevons	815	
	Tip fins	281	
	Body flap	615	
13.0	Avionics		3 290
	Guidance, navigation, & control	496	
	Communication & tracking	754	
	Displays & controls	1 049	
	Instrument systems	332	
	Data processing	659	
14.0	Environmental control		1 500
	Personnel system	524	
	Equipment cooling	170	
	Heat-transfer loop	628	
	Heat-rejection system	44	
	Supports and install	134	
15.0	Personnel provisions		1 375
	Food, waste mgmt	555	
	Seats	820	
16.0	Margin		11 781
	Dry weight		**159 329**
17.0	Personnel		3 306
	Crew & gear	2 130	
	Accessories	1 176	
18.0	Payload canister & shroud		14 260
19.0	Cargo (returned)		12 000
20.0	Residual fluids		6 738
	OMS & RCS	1 264	
	Ascent	4 980	
	Subsystems	494	
21.0	Reserves		1 138
	OMS	512	
	RCS	626	
	APU	0	
	Landed weight		**196 770**
22.0	RCS propellant (entry)		664
	Entry weight		**197 434**
23.0	On-orbit propellant		12 754
	RCS	1 540	
	OMS	11 214	
24.0	Cargo delivered		0
25.0	Ascent reserves		3 949
26.0	In-flight losses		5 486
	Fuel cell reactant	459	
	APU exhaust	0	
	Evaporator water supply	3 108	
	Helium purge gas	1 919	

27.0	Ascent propellant		1 044 779
	CH_4	0	
	LH_2	139 582	
	LOX	905 197	
	Gross lift-off weight		**1 264 402**
28.0	Prelaunch start-up losses		0
	Orbiter LH_2	0	
	Orbiter LOX	0	
	Booster CH_4	0	
	Booster LOX	0	
	Gross prelaunch weight		**1 264 402**

Orbiter geometry—LOX/LH_2

Body length, ft	140.9
Body structure wetted area, ft^2	16 027.4
Body volume, ft^3	72 524.3
Tank efficiency factor	0.722
Base area, ft^2	713.0
Engine compartment length, ft	12.0
Aft perimeter, ft	103.4
Nose area, ft^2	2175.6
Forward intertank area, ft^2	2558.2
Rear intertank area, ft^2	1797.0
Aft engine fairing, ft^2	1235.0
Exposed wing area, ft^2	2215.9
Wing span, ft	100.6
Structural span, ft	84.4
Body width, ft	34.6
Max wing root thickness, ft	5.3
Vertical tip fin area, ft^2	213.4
Rudder/speedbrake area, ft^2	93.1
Elevon area, ft^2	402.3
Body flap area, ft^2	251.7
LH_2 propellant fraction	0.1336
LOX propellant fraction	0.8664
LOX tank volume, ft^3	13 278
LH_2 tank volume, ft^3	32 907
Percent tank ullage	4.25

Shuttle II
Two-Stage Fully Reusable Vehicle

Booster weights—LOX/CH_4/LH_2

Group number	Group	Weight, lb	
		Subgroup	Group
1.0	Wing		8 485
	Exposed wing	6 773	
	Carry-through	1 712	
2.0	Tail		335
3.0	Body		38 760
	LOX tank	10 654	
	LH_2 tank + insulation	8 772	
	CH_4 tank	4 068	
	Basic structure	2 334	
	Thrust structure	3 078	
	Intertank 1	3 815	
	Intertank 2	3 750	
	Intertank 3	2 029	
	Body flap	260	
4.0	Thermal protection system		0
4.5	Helium purge system		1 467
5.0	Landing gear/separation system		4 341
	Landing gear	3 471	
	Separation	870	
6.0	Propulsion		37 692
	Powerheads	20 337	
	Nozzles	2 294	
	Pressurization & feed	11 805	
	Gimbals	2 460	
	Crossfeed	796	
7.0	Propulsion, RCS		1 275
8.0	Propulsion, OMS		0
	Engines	0	
	Feed lines	0	
	Pressurization	0	
9.0	Prime power		1 615
	Fuel cells	0	
	Batteries	1 615	
10.0	Elec conversion & distribution		3 166
	Power conversion	772	
	Avionics cabling	1 547	
	Elec surface control cabling	847	
11.0	Hydraulics		0
12.0	Electric actuators		1 035
	Elevons	667	
	Tip fins	91	
	Body flap	277	
13.0	Avionics		2 433
	Guidance, navigation, & control	468	
	Communication & tracking	419	
	Displays & controls	555	

	Instrument systems	332	
	Data processing	659	
14.0	Environmental control		696
	Personnel system	0	
	Equipment cooling	170	
	Heat-transfer loop	526	
	Heat-rejection system	0	
	Supports and install	0	
15.0	Personnel provisions		0
	Food, waste mgmt	0	
	Seats	0	
16.0	Margin		6 361
	Dry weight		**107 661**
17.0	Personnel		0
	Crew & gear	0	
	Accessories	0	
18.0	Payload canister & shroud		0
19.0	Cargo (returned)		0
20.0	Residual fluids		7 840
	RCS	81	
	Ascent	7 469	
	Subsystems	290	
21.0	Reserves		78
	OMS	0	
	RCS	78	
	APU	0	
	Landed weight		**115 579**
22.0	RCS propellant (entry)		390
	Entry weight		**115 969**
23.0	On-orbit propellant		0
	RCS	0	
	OMS	0	
24.0	Cargo delivered		1 264 401
25.0	Ascent reserves		2 319
26.0	In-flight losses		1 470
	Fuel cell reactant	3	
	APU exhaust	0	
	Evaporator water supply	0	
	Helium purge gas	1 467	
27.0	Ascent propellant		1 071 045
	CH_4	138 823	
	LH_2	64 616	
	LOX	867 606	
	Gross lift-off weight		**2 455 204**

28.0	Prelaunch start-up losses		37 493
	Orbiter LH_2	1 887	
	Orbiter LOX	12 230	
	Booster CH_4	4 932	
	Booster LOX	18 444	
	Gross prelaunch weight		**2 492 697**

Booster geometry—LOX/CH_4/LH_2

Body length, ft	118.0
Body volume, ft^3	55 904.4
Tank efficiency factor	0.708
Base area, ft^2	585.0
Engine compartment length, ft	12.0
Aft perimeter, ft	91.4
Nose area, ft^2	10.5
Forward intertank area, ft^2	1809.9
Rear intertank area, ft^2	1779.1
Aft engine fairing, ft^2	962.7
Exposed wing area, ft^2	1489.2
Wing span, ft	80.5
Structural span, ft	67.0
Body width, ft	25.7
Max wing root thickness, ft	4.6
Vertical tip fin area, ft^2	114.4
Rudder/speedbrake area, ft^2	44.0
Elevon area, ft^2	351.8
Body flap area, ft^2	148.0
CH_4 propellant fraction	0.1296
LH_2 propellant fraction	0.0603
LOX propellant fraction	0.8101
CH_4 tank volume, ft^3	5663
LOX tank volume, ft^3	13 172
LH_2 tank volume, ft^3	15 767
Percent tank ullage	4.25

Shuttle II
Heavy-Lift Expendable Vehicle

Core stage weights—LOX/LH_2

Group	Weight, lb	
	Subgroup	Group
Body		41 882
LOX tank	12 570	
LH_2 tank	21 564	
Intertank	3 921	
Aft intertank	1 540	
Forward skirt	2 287	
Rear thrust truss		1 318
Thermal protection		1 192
Skirts & intertank	96	
LOX tank	88	
LH_2 tank	1 008	
Separation system		784
Propulsion, main (core)		8 004
Pressurization & feed (80%)	7 130	
Crossfeed	874	
Elec conversion & distribution (50%)		129
Body margin		5 331
Core dry weight	**58 640**	
P/A module body structure		15 162
P/A base shield		1 008
P/A thermal protection		2 571
P/A separation system		35
Propulsion, main (P/A)		28 164
Main engines	24 163	
Pressurization & feed (20%)	1 783	
Gimbals	2 218	
Propulsion, OMS & RCS		1 028
OMS engines	326	
OMS tanks	121	
RCS engines	33	
Feed lines	208	
Pressurization	340	
Prime power (P/A)		1 309
APU, engine gimbals	404	
Batteries	905	
Elec conversion & distribution (50%)		129
Hydraulics conversion & distribution		819
Avionics		450
Environmental control		178
P/A module recovery system		3 412
P/A module margin		2 788
P/A module dry weight	**57 053**	
Total dry weight		**115 693**

Payload		150 000
Payload support		7 500
Residual fluids		6 361
OMS & RCS	436	
Ascent	5 925	
Ascent reserves		6 258
On-orbit propellant		4 848
OMS burn 1	3 736	
OMS burn 2	1 112	
Insertion weight		**290 660**
Inflight losses		17 003
Payload shroud	15 457	
Payload shroud margin	1 546	
Ascent propellant		1 346 582
LH_2	179 964	
LOX	1 166 618	
Gross lift-off weight		**1 654 255**

Core stage geometry—LOX/LH_2

	Subgroup	Group
Stage diameter, ft		25.7
Stage height, ft		259.4
Nose cap, ft	30.0	
Payload fairing, ft	72.6	
Forward skirt, ft	13.5	
LOX tank cylinder, ft	21.3	
Intertank, ft	23.1	
LH_2 tank cylinder, ft	70.8	
Aft intertank, ft	9.1	
P/A module, ft	14.0	
Exposed engines, ft	5.0	
LOX tank volume, ft^3		17 273
LH_2 tank volume, ft^3		42 825

Appendix B

Shuttle II Mass-Estimating Relationship

Appendix B contains the mass estimating relationships (MER's) used to calculate the weights of the reference Shuttle II booster, orbiter, and core vehicles. Each vehicle subsystem is modeled as an MER in the AVID weights and sizing program. These equations are contained within a sizing loop that geometrically scales the vehicle with respect to mass ratio. Each equation is then multiplied by a technology factor, where appropriate, that represents the perceived benefit of applying evolutionary (from STS) technologies to that subsystem. A more detailed discussion of similar MER's is contained in reference 22.

The following list of symbols contains symbols used only in appendix B:

ALH2CYL	liquid hydrogen tank cylinder surface area, ft^2
ALH2DOME	liquid hydrogen tank dome surface area, ft^2
ALOXCYL	liquid oxygen tank cylinder surface area, ft^2
ALOXDOME	liquid oxygen tank dome surface area, ft^2
AR	aspect ratio of wing
BBODY	body width, ft
BODVOL	vehicle body volume, ft^3
BSTR	structural span of wing, ft
DELV	total change in velocity for ascent, ft/sec
DIA	vehicle diameter, ft
e	natural logarithm base, 2.718
GO	acceleration of gravity, 34.174 ft/sec^2
ISPO	specific impulse of OMS engines, sec
ISPVAC	vacuum specific impulse of main engines, sec
ISPVACORB	vacuum specific impulse of orbiter main engines, sec
LAFTINT	aft intertank length, ft
LBAY	engine bay length, ft
LBODY	total vehicle body length, ft
LFS	forward skirt length, ft
LINT	forward intertank length, ft
NCREW	number of crew
PAFT	perimeter of vehicle base, ft
PAVP	peak avionics power, kW
PF1	liquid oxygen propellant fraction
PF2	liquid hydrogen propellant fraction
PF3	methane propellant fraction
PFC	fuel cell power, kW
PRELOSS	total propellant prelaunch loss weight, lb
QMAX	maximum dynamic pressure, lb/ft^2
RHOCH4	methane density, 26.5 lb/ft^3
RHOLH2	liquid hydrogen density, 4.43 lb/ft^3
RHOLOX	liquid oxygen density, 71.2 lb/ft^3
RMIX	oxidizer-to-fuel ratio
RMIXORB	oxidizer-to-fuel ratio of orbiter
SBASE	vehicle base area, ft^2
SBF	body flap planform area, ft^2
SEL	elevon planform area, ft^2
SEXP	exposed wing area, ft^2
SINT	surface area of first intertank, ft^2
SINT2	surface area of second intertank, ft^2
SINT3	surface area of third intertank, ft^2
SNOSE	nose surface area, ft^2
SPLAN	vehicle planform area, ft^2
SRDSB	rudder/speed brake planform area, ft^2
STF	tip fin planform area, ft^2
SWET	total vehicle wetted area, ft^2
TANVOL	total volume of main propellant tanks, ft^3

TCOTR	taper ratio of wing
TDAY	mission duration, days
TOC	thickness-to-chord ratio of wing
TOW	vehicle lift-off thrust-to-weight ratio
TROOT	maximum root thickness of wing, ft
TSTART	start-up time for main engines, sec
TVAC	vacuum thrust of main engines, lb
TVACORB	vacuum thrust of orbiter main engines, lb
ULLAGE	propellant tank percent ullage
VOMS1	velocity required for first OMS burn, ft/sec
VOMS2	velocity required for second OMS burn, ft/sec
WACTOR	electric actuators weight, lb
WBO	vehicle weight at nominal insertion, lb
WCH4	methane fuel weight, lb
WDOT	fuel cell reactant flow rate, lb/sec
WDRY	vehicle dry weight, lb
WENG	main propulsion system weight, lb
WENTRY	vehicle weight upon reentry, lb
WFCROP	fuel cell reactant weight, lb
WGORB	gross lift-off weight of orbiter, lb
WGROSS	vehicle gross lift-off weight, lb
WH2O	flash evaporator water weight, lb
WINF	weight of inflight losses, lb
WLAND	vehicle landed weight, lb
WLH2	liquid hydrogen weight, lb
WLOSCH4	methane prelaunch losses weight, lb
WLOSLH2	liquid hydrogen prelaunch losses weight, lb
WLOSLOX	liquid oxygen prelaunch losses weight, lb
WLOX	liquid oxygen weight, lb
WMARG	vehicle margin weight, lb
WMARPA	P/A module margin weight, lb
WOMSENG	OMS engine weight, lb
WOMSPROP	OMS propellant weight, lb
WPADRY	P/A module dry weight, lb
WPROP	total ascent propellant weight, lb
WPL	vehicle payload weight, lb
WPLSD	payload shroud weight, lb
WPH	total engine powerhead weight, lb
XMR	desired mass ratio

Shuttle II
Two-Stage Fully Reusable Vehicle

Orbiter weights—LOX/LH_2

Group number	Group	Mass-estimating relationship
1.0	Wing	
	Exposed wing	$0.8295 \times (0.001 \times 1.5 \times 0.53 \times \text{QMAX} \times \text{SEXP})^{0.48} \times \text{SEXP}^{0.67} \times \text{AR}^{0.64} \times [(1 + \text{TCOTR})/\text{TOC}]^{0.4} \times (1 - 0.44)$
	Carry-through	$319.3 \times 0.001 \times 1.5 \times 0.53 \times \text{QMAX} \times \text{SEXP} \times \text{BSTR} \times [\text{AR} \times (1 + \text{TCOTR})]^{0.5} \times \text{BBODY} \times 0.0000166 \times 1.2 \times (1 - 0.44)/\text{TROOT}$
2.0	Tail	$1.678 \times \text{STF}^{1.24} \times (1 - 0.44)$
3.0	Body	
	LOX tank	$0.8086 \times 1.1 \times \text{WLOX} \times (1 - 0.1)/[\text{RHOLOX} \times (1 - \text{ULLAGE})]$
	LH_2 tank + installation	$0.5595 \times 1.1 \times \text{WLH2} \times (1 - 0.1)/[\text{RHOLH2} \times (1 - \text{ULLAGE})]$
	Nose section	$3.4 \times \text{SNOSE} \times (1 - 0.38)$
	Aft section	$3.4 \times \text{PAFT} \times \text{LBAY} \times (1 - 0.38)$
	Access tunnel	$3.14159 \times 4 \times 27 \times 1$
	Tunnel fairing	$13.7 \times 27 \times 2$
	Thrust structure	$0.0023 \times \text{TVAC} \times (1 - 0.38)$
	Crew cabin	$1.5 \times 2347 \times \text{NCREW}^{0.5} \times (1 - 0.38)$
	Body flap	$3.135 \times \text{SBF} \times (1 - 0.44)$
	Intertank 1	$3.4 \times \text{SINT} \times (1 - 0.38)$
	Intertank 2	$3.4 \times \text{SINT2} \times (1 - 0.38)$
4.0	Thermal protection system	$0.14 \times \text{WENTRY}^{0.5} \times \text{SWET} \times (1 - 0.35)/(0.1^{0.302} \times \text{SPLAN}^{0.5} \times 0.65^{0.5})$
4.5	Helium purge system	$0.3 \times (\text{BODVOL} - \text{SBASE} \times \text{LBAY})$
5.0	Landing gear/separation system	
	Landing gear	$0.033 \times \text{WLAND} \times (1 - 0.09)$
	Separation	$0.00065 \times \text{TVAC} \times (1 - 0.38)$
6.0	Propulsion	
	Powerheads	$0.01133699 \times \text{TVAC}$
	Nozzles	$\text{WPH} \times 0.01194 \times 59/5$

	Pressurization and feed	$2.02 \times TVAC/ISPVAC$
	Gimbals	$0.00114 \times TVAC$
	Crossfeed	$0.198 \times TVAC/ISPVAC$
7.0	Propulsion, RCS	$0.0001035 \times WENTRY \times LBODY$
8.0	Propulsion, OMS	
	Engines	$0.001456 \times WENTRY$
	Feed lines	$0.039 \times 1.614 \times WOMSPROP$
	Pressurization	340
9.0	Prime power	
	Fuel cells	$89.5 \times PAVP \times 2$
	Reactant dewers	$0.76 \times WFCROP \times 2$
	Batteries (surface controls)	$0.5 \times 0.007 \times WDRY$
	Batteries (gimbals)	$0.5 \times 0.007 \times WDRY$
10.0	Elec conversion & distribution	
	Power conversion	$313.7 \times PAVP \times (1 - 0.18)$
	Avionics cabling	$5.33 \times PAVP \times LBODY \times (1 - 0.18)$
	Elec surface control cabling	$0.00846 \times WACTOR \times LBODY \times (1 - 0.18)$
12.0	Electric actuators	
	Elevon	$0.101 \times SEL^{1.5}$
	Tip fin	$0.313 \times SRDSB^{1.5}$
	Body flap	$0.154 \times SBF^{1.5}$
13.0	Avionics	
	Guidance, navigation, & control	$992 \times (1 - 0.5)$
	Communication & tracking	$1507 \times (1 - 0.5)$
	Displays & controls	$2809 \times (1 - 0.5)$
	Instrument systems	$664 \times (1 - 0.5)$
	Data processing	$1317 \times (1 - 0.5)$
14.0	Environmental control	
	Personnel system	$(81 + 0.295 \times 24 \times TDAY) \times NCREW \times (1 - 0.1)$

	Equipment cooling	$63 \times \mathrm{PAVP} \times (1 - 0.1)$
	Heat-transfer loop	$1.65 \times \mathrm{PAVP} \times \mathrm{LBODY} \times (1 - 0.1)$
	Heat-rejection system	$16.2 \times \mathrm{PAVP} \times (1 - 0.1)$
	Supports and install	$0.048 \times \mathrm{WH2O} \times (1 - 0.1)$
15.0	Personnel provisions	
	Food, waste mgmt	555
	Seats	$164 \times \mathrm{NCREW}$
16.0	Margin	$0.1 \times (\mathrm{WDRY} - \mathrm{WENG} - \mathrm{WMARG})$
17.0	Personnel	
	Crew & gear	$(311 + 0.958 \times 24 \times \mathrm{TDAY}) \times \mathrm{NCREW}$
	Accessories	1176
18.0	Payload canister & shroud	$23\,000 \times (1 - 0.38)$
19.0	Cargo (returned)	12 000
20.0	Residual fluids	
	OMS & RCS	$0.0064 \times \mathrm{WENTRY}$
	Ascent	$0.0039 \times \mathrm{TOW} \times \mathrm{WGROSS}$
	Subsystems	$0.0025 \times \mathrm{WENTRY}$
21.0	Reserves	
	OMS	$0.0026 \times \mathrm{WLAND}$
	RCS	$0.00318 \times \mathrm{WLAND}$
22.0	RCS propellant (entry)	$0.003363 \times \mathrm{WENTRY}$
23.0	On-orbit propellant	
	RCS	$0.0078 \times \mathrm{WENTRY}$
	OMS	$0.0568 \times \mathrm{WENTRY}$
25.0	Ascent reserves	$0.02 \times \mathrm{WENTRY}$
26.0	In-flight losses	
	Fuel cell reactant	$1.65 \times \mathrm{PFC} \times \mathrm{WDOT} \times 24 \times (\mathrm{TDAY} + 0.5)$
	Evaporator water supply	$3.5 \times \mathrm{PFC} \times (\mathrm{TDAY} + 0.5) \times 24/0.55$
	Helium purge gas	$0.03 \times (\mathrm{BODVOL} - \mathrm{SBASE} \times \mathrm{LBAY})$

27.0	Ascent propellant	
	LH_2	PF2 × [TANVOL × (1 − ULLAGE)]/ [(PF1/RHOLOX + PF2/RHOLH2)]
	LOX	PF1 × [TANVOL × (1 − ULLAGE)]/ [(PF1/RHOLOX + PF2/RHOLH2)]

Shuttle II
Two-Stage Fully Reusable Vehicle

Booster weights—$LOX/CH_4/LH_2$

Group number	Group	Mass-estimating relationship
1.0	Wing	
	Exposed wing	$0.8295 \times (0.001 \times 1.5 \times 0.53 \times \mathrm{QMAX} \times \mathrm{SEXP})^{0.48} \times \mathrm{SEXP}^{0.67} \times \mathrm{AR}^{0.64} \times [(1 + \mathrm{TCOTR})/\mathrm{TOC}]^{0.4} \times (1 - 0.44)$
	Carry-through	$319.3 \times 0.001 \times 1.5 \times 0.53 \times \mathrm{QMAX} \times \mathrm{SEXP} \times \mathrm{BSTR} \times [\mathrm{AR} \times (1 + \mathrm{TCOTR})]^{0.5} \times \mathrm{BBODY} \times 0.0000166 \times 1.14 \times (1 - 0.44)/\mathrm{TROOT}$
2.0	Tail	$1.678 \times \mathrm{STF}^{1.24} \times (1 - 0.44)$
3.0	Body	
	LOX tank	$0.8086 \times 1.1 \times (\mathrm{WLOX} + \mathrm{WLOSLOX}) \times (1 - 0.1)/[\mathrm{RHOLOX} \times (1 - \mathrm{ULLAGE})]$
	LH_2 tank + installation	$0.5595 \times 1.1 \times (\mathrm{WLH2} + \mathrm{WLOSLH2}) \times (1 - 0.1)/[\mathrm{RHOLOH2} \times (1 - \mathrm{ULLAGE})]$
	CH_4 tank	$0.718 \times 1.1 \times (\mathrm{WCH4} + \mathrm{WLOSCH4}) \times (1 - 0.1)/[\mathrm{RHOCH4} \times (1 - \mathrm{ULLAGE})]$
	Nose section	$3.4 \times \mathrm{SNOSE} \times (1 - 0.38)$
	Aft section	$3.4 \times \mathrm{PAFT} \times \mathrm{LBAY} \times (1 - 0.38)$
	Thrust structure	$0.0023 \times \mathrm{TVAC} \times (1 - 0.38)$
	Intertank 1	$3.4 \times \mathrm{SINT} \times (1 - 0.38)$
	Intertank 2	$3.4 \times \mathrm{SINT2} \times (1 - 0.38)$
	Intertank 3	$3.4 \times \mathrm{SINT3} \times (1 - 0.38)$
	Body flap	$3.135 \times \mathrm{SBF} \times (1 - 0.44)$
4.5	Helium purge system	$0.03 \times (\mathrm{BODVOL} - \mathrm{SBASE} \times \mathrm{LBAY})$
5.0	Landing gear/separation system	
	Landing gear	$0.033 \times \mathrm{WLAND} \times (1 - 0.09)$
	Separation	$0.00065 \times \mathrm{TVAC} \times (1 - 0.38)$
6.0	Propulsion	
	Powerheads	$0.00942278 \times \mathrm{TVAC}$
	Nozzles	$\mathrm{WPH} \times 0.00727 \times 54/3.48$

	Pressurization and feed	$2.02 \times WPH/3.48$
	Gimbals	$0.00114 \times TVAC$
	Crossfeed	$0.198 \times WGORB \times 1.15/ISPVAC$
7.0	Propulsion, RCS	$0.0001035 \times WENTRY \times LBODY \times (1 - 0.1)$
9.0	Prime power	
	Batteries (gimbals)	$0.000065 \times TVAC \times 2$
	Batteries (surface controls)	$0.085 \times WACTOR \times 2$
10.0	Elec conversion & distribution	
	Power conversion	$313.7 \times PAVP \times (1 - 0.18)$
	Avionics cabling	$5.33 \times PAVP \times LBODY \times (1 - 0.18)$
	Elec surface control cabling	$0.00846 \times WACTOR \times LBODY \times (1 - 0.18)$
12.0	Electric actuators	
	Elevon	$0.101 \times SEL^{1.5}$
	Tip fin	$0.313 \times SRDSB^{1.5}$
	Body flap	$0.154 \times SBF^{1.5}$
13.0	Avionics	
	Guidance, navigation, & control	$936 \times (1 - 0.5)$
	Communication & tracking	$837 \times (1 - 0.5)$
	Displays & controls	$1110 \times (1 - 0.5)$
	Instrument systems	$664 \times (1 - 0.5)$
	Data processing	$1317 \times (1 - 0.5)$
14.0	Environmental control	
	Equipment cooling	$63 \times PAVP \times (1 - 0.1)$
	Heat-transfer loop	$1.65 \times PAVP \times LBODY \times (1 - 0.1)$
16.0	Margin	$0.1 \times (WDRY - WENG - WMARG)$
20.0	Residual fluids	
	RCS	$0.0007 \times WENTRY$
	Ascent	$0.0039 \times TOW \times WGROSS$
	Subsystems	$0.0025 \times WENTRY$

21.0	RCS reserves	$0.2 \times \text{WENTRY} \times 0.003363$
22.0	RCS propellant (entry)	$0.003363 \times \text{WENTRY}$
24.0	Cargo delivered	WGORB
25.0	Ascent reserves	$0.02 \times \text{WENTRY}$
26.0	In-flight losses	
	Fuel cell reactant	$1.65 \times \text{PFC} \times \text{WDOT} \times 1$
	Helium purge gas	$0.03 \times (\text{BODVOL} - \text{SBASE} \times \text{LBAY})$
27.0	Ascent propellant	
	CH_4	$\text{PF3} \times \{\text{TANVOL} \times (1 - \text{ULLAGE})/[(\text{PF1}/\text{RHOLOX} + \text{PF2}/\text{RHOLH2} + \text{PF3}/\text{RHOCH4}) - \text{PRELOSS}]\}$
	LH_2	$\text{PF2} \times \{\text{TANVOL} \times (1 - \text{ULLAGE})/[(\text{PF1}/\text{RHOLOX} + \text{PF2}/\text{RHOLH2} + \text{PF3}/\text{RHOCH4}) - \text{PRELOSS}]\}$
	LOX	$\text{PF1} \times \{\text{TANVOL} \times (1 - \text{ULLAGE})/[(\text{PF1}/\text{RHOLOX} + \text{PF2}/\text{RHOLH2} + \text{PF3}/\text{RHOCH4}) - \text{PRELOSS}]\}$
28.0	Prelaunch start-up losses	
	Orbiter LH_2	$\text{TVACORB} \times \text{TSTART}/[\text{ISPVACORB} \times (\text{RMIXORB} + 1)]$
	Orbiter LOX	$\text{WLOSLH2} \times \text{RMIXORB}$
	Booster CH_4	$\text{TVAC} \times \text{TSTART}/[\text{ISPVAC} \times (\text{RMIX} + 1)]$
	Booster LOX	$\text{WLOSCH4} \times \text{RMIX}$

Shuttle II
Heavy-Lift Expendable Vehicle

Core stage weights—LOX/LH_2

Group	Mass-estimating relationship
Body group	
LOX tank	0.8086 × WLOX × (1 − 0.1)/[RHOLOX × (1 − ULLAGE)]
LH_2 tank	0.5595 × WLH2 × (1 − 0.1)/[RHOLH2 × (1 − ULLAGE)]
Intertank	3.4 × LINT × 3.14159 × DIA × (1 − 0.38)
Aft intertank	3.4 × LAFTINT × 3.14159 × DIA × (1 − 0.38)
Forward skirt	3.4 × LFS × 3.14159 × DIA × (1 − 0.38)
Rear thrust truss	0.08 × 0.01366 × TVAC × (1 − 0.38)
Thermal protection system	
Skirts & intertank	0.04 × 3.14159 × DIA × (LFS + LINT + LAFTINT) × (1 − 0.35)
LOX tank	0.04 × (ALOXDOME + ALOXCYL) × (1 − 0.35)
LH_2 tank	0.21 × (ALH2DOME + ALH2CYL) × (1 − 0.35)
Separation system	0.00065 × TVAC × (1 − 0.38)
Propulsion, main (core)	
Pressurization & feed (80%)	0.8 × 2.02 × TVAC/ISPVAC
Crossfeed	0.198 × TVAC/ISPVAC
Elec conversion & distribution (50%)	0.5 × 313.7 × (1 − 0.18)
Body margin	0.1 × (WDRY − WMARG)
P/A module body structure	0.92 × 0.01366 × TVAC × (1 − 0.38)
P/A module base shield	3 × 3.14159 × DIA × DIA/4 × (1 − 0.35)
P/A module thermal protection	0.24 × [0.01366 × TVAC × (1 − 0.38)] × (1 − 0.35)
P/A separation system	35
Propulsion, main (P/A)	
Main engines	0.012417 × TVAC
Pressurization & feed (20%)	0.2 × 2.02 × TVAC/ISPVAC
Gimbals	0.00114 × TVAC

Propulsion, OMS & RCS	
OMS engines	$0.00112 \times \mathrm{WBO}$
OMS tanks	$\{0.5595 \times [\mathrm{WOMSPROP}/(7 \times \mathrm{RHOLH2})] + 0.8086 \times [6 \times \mathrm{WOMSPROP}/(7 \times \mathrm{RHOLOX})]\} \times (1 - 0.1)$
RCS engines	$0.1 \times \mathrm{WOMSENG}$
Feed lines	$1.1 \times 0.039 \times \mathrm{WOMSPROP}$
Pressurization	340
Prime power (P/A)	
APU, engine gimbals	$0.0002077 \times \mathrm{TVAC}$
Batteries	905
Elec conversion & distribution (50%)	$0.5 \times 313.7 \times (1 - 0.18)$
Hydraulics conversion & distribution	$0.000421 \times \mathrm{TVAC}$
Avionics	$900 \times (1 - 0.5)$
Environmental control	$0.44 \times 900 \times (1 - 0.1)$
P/A module recovery system	$0.598 \times \mathrm{WPADRY}$
P/A module margin	$0.1 \times (\mathrm{WPADRY} - \mathrm{WMARPA} - \mathrm{WENG})$
Payload	150 000
Payload support	$0.05 \times \mathrm{WPL}$
Residual fluids	
OMS & RCS	$0.0015 \times \mathrm{WBO}$
Ascent	$0.0044 \times \mathrm{WPROP}$
Ascent reserves	$\mathrm{WBO} \times (e^{[\mathrm{DELV} \times 0.01/(\mathrm{ISPVAC} \times \mathrm{GO})]} - 1)$
On-orbit propellant	
OMS burn 1	$\mathrm{WBO} \times (e^{[\mathrm{VOMS1}/(\mathrm{ISPO} \times \mathrm{GO})]} - 1)$
OMS burn 2	$\mathrm{WPADRY} \times (e^{[\mathrm{VOMS2}/(\mathrm{ISPO} \times \mathrm{GO})]} - 1)$
In-flight losses	
Payload shroud	$(3.5 \times 1275 + 3.5 \times \mathrm{WPL}/\mathrm{DIA}) \times (1 - 0.38)$
Payload shroud margin	$0.1 \times \mathrm{WPLSD}$
Ascent propellant	
LH_2	$[\mathrm{WBO} \times (\mathrm{XMR} - 1) - \mathrm{WINF}]/(1 + \mathrm{RMIX})$
LOX	$\mathrm{RMIX} \times [\mathrm{WBO} \times (\mathrm{XMR} - 1) - \mathrm{WINF}]/(1 + \mathrm{RMIX})$

Appendix C

Shuttle II Ascent Trajectory Plots

Appendix C contains ascent trajectory plots for the reference Shuttle II booster-orbiter configuration. The reference mission is to deliver 12 000 lb of payload to a 150 nmi circular, 98.0° inclination orbit with a nominal insertion orbit of 50 × 100 nmi. The six variables that are plotted, respectively, against time are altitude, relative velocity, acceleration, relative flight-path angle, angle of attack, and dynamic pressure. (See figs. C1 through C6.) An axial acceleration constraint of $3g$ is held throughout the trajectory. The angle of attack remains between $-7°$ and $12°$, and a maximum dynamic pressure constraint of 800 psf is assumed. In addition, the normal force on both the booster and orbiter is held to 2.5 times the landed weight for each vehicle.

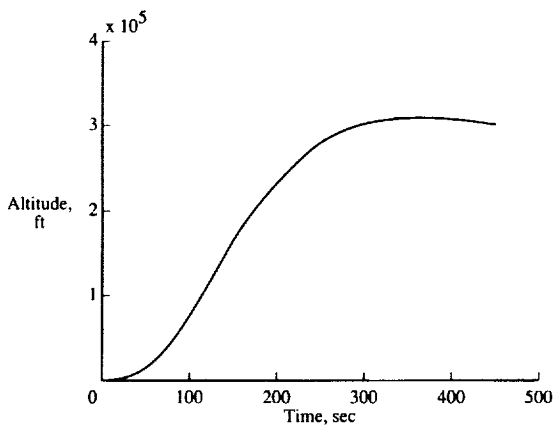

Figure C1. Altitude profile of reference fully reusable Shuttle II vehicle.

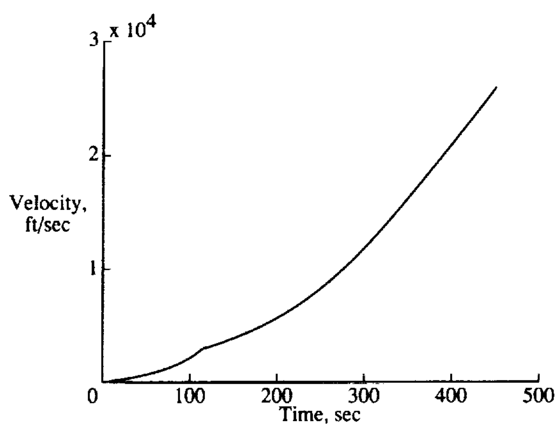

Figure C2. Velocity profile of reference fully reusable Shuttle II vehicle.

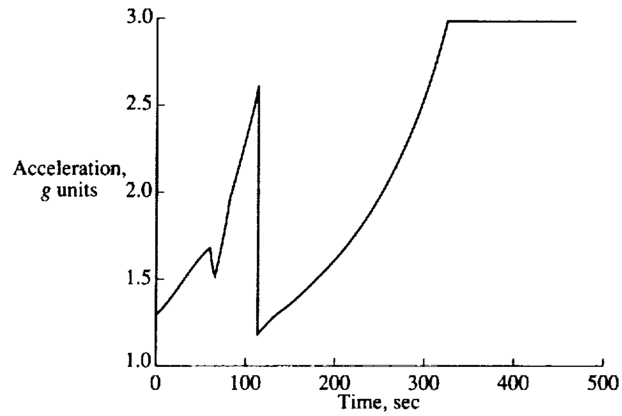

Figure C3. Acceleration profile of reference fully reusable Shuttle II vehicle.

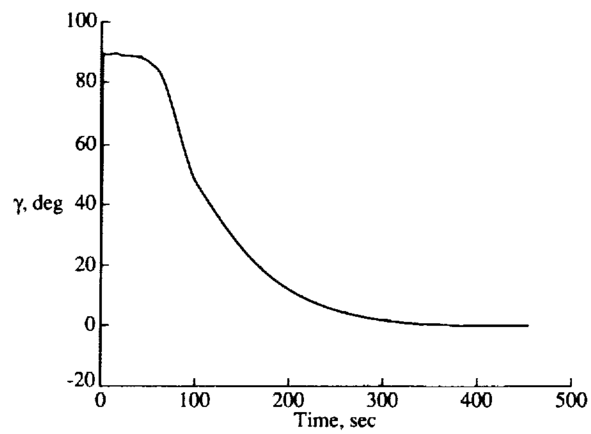

Figure C4. Flight-path angle profile of reference fully reusable Shuttle II vehicle.

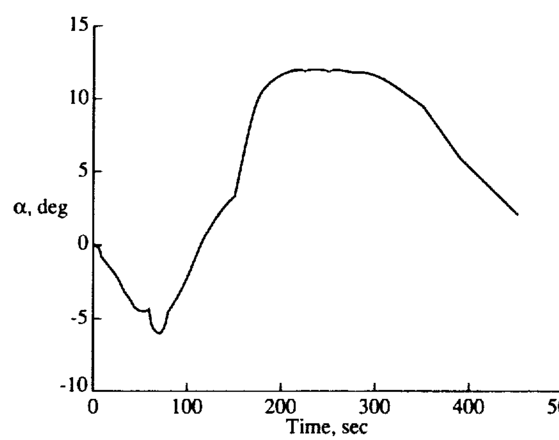

Figure C5. Angle-of-attack profile of reference fully reusable Shuttle II vehicle.

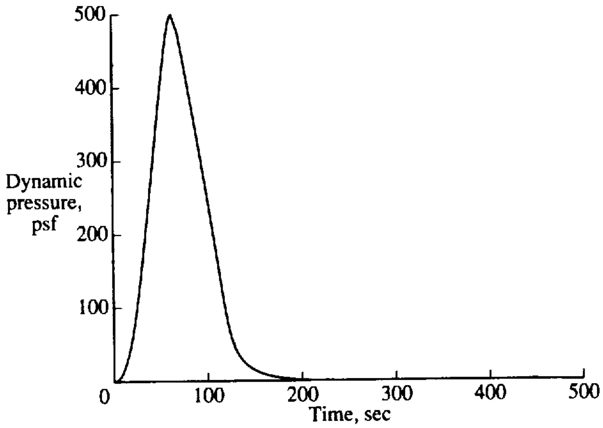

Figure C6. Dynamic pressure profile of reference fully reusable Shuttle II vehicle.

Appendix D

Shuttle II Aerodynamic Characteristics

Appendix D contains plots of C_L and C_D with respect to angle of attack and Mach number for the reference Shuttle II orbiter, booster, and core vehicles. (See figs. D1 through D17.) The aerodynamic data base used in this study was developed using the Aerodynamic Preliminary Analysis System (APAS). (See ref. 6.) In the subsonic and low supersonic speed ranges, APAS utilizes slender body theory, viscous and wave drag empirical techniques, and source and vortex panel distributions to estimate the vehicle aerodynamics. At high supersonic and hypersonic speeds, a noninterference finite element model of the vehicle is analyzed with empirical impact pressure methods and approximate boundary-layer methods. Included in this high-speed analysis are real-gas viscous effects and boundary-layer transition. For the orbiter, booster, and core the respective reference lengths used by APAS were 140.9, 118.0, and 259.3 ft. The respective reference areas used were 2215.9, 1489.2, and 518.8 ft^2.

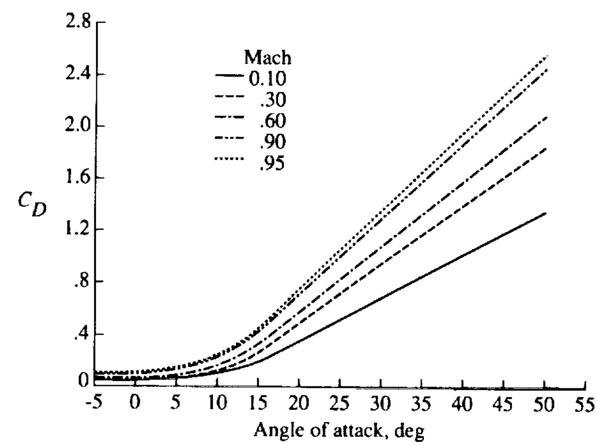

Figure D1. Drag coefficient variation for reference Shuttle II orbiter for Mach 0.10 to 0.95.

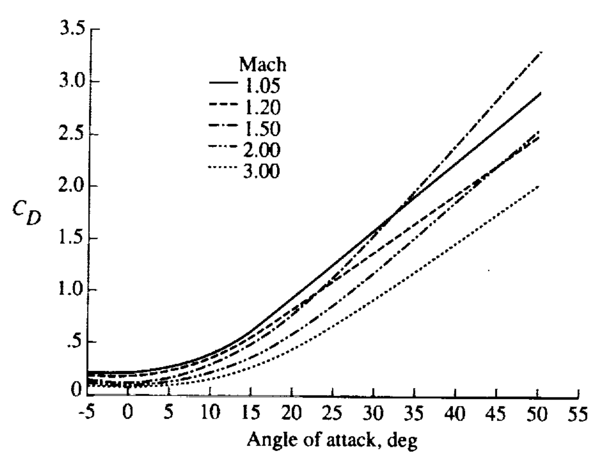

Figure D2. Drag coefficient variation for reference Shuttle II orbiter for Mach 1.05 to 3.00.

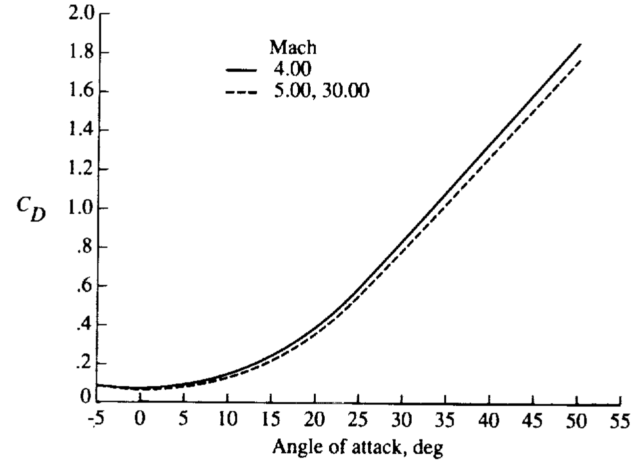

Figure D3. Drag coefficient variation for reference Shuttle II orbiter for Mach 4.00, 5.00, and 30.00.

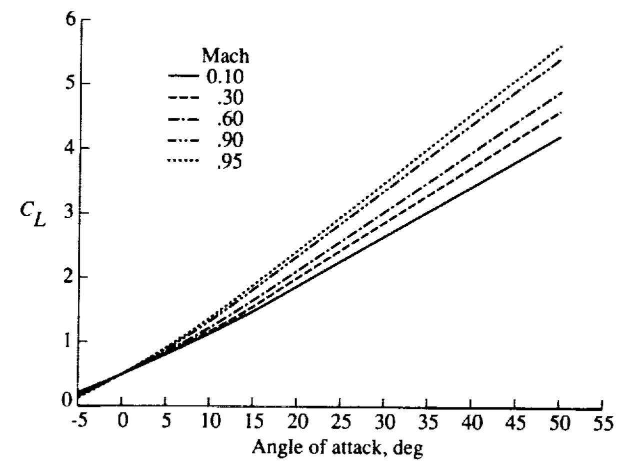

Figure D4. Lift coefficient variation for reference Shuttle II orbiter for Mach 0.10 to 0.95.

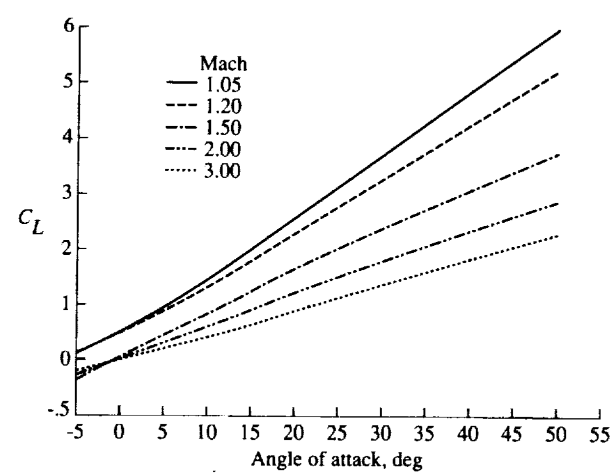

Figure D5. Lift coefficient variation for reference Shuttle II orbiter for Mach 1.05 to 3.00.

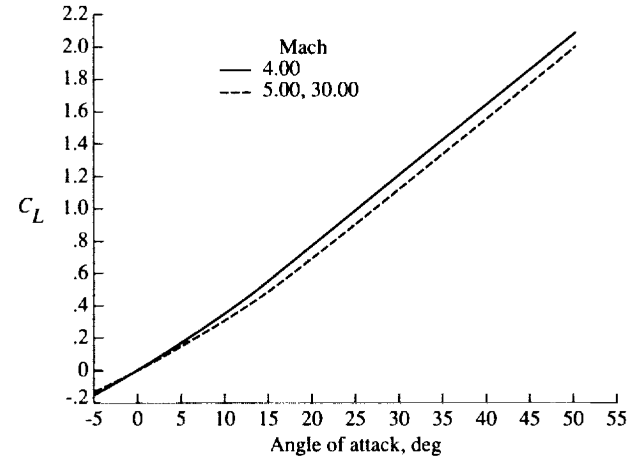

Figure D6. Lift coefficient variation for reference Shuttle II orbiter for Mach 4.00, 5.00, and 30.00.

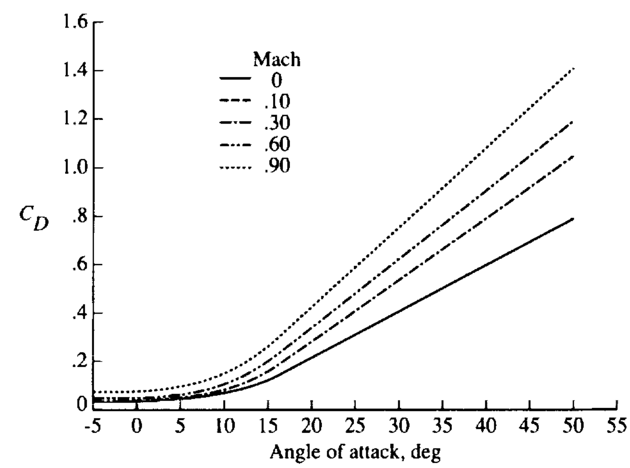

Figure D7. Drag coefficient variation for reference Shuttle II booster for Mach 0 to 0.90.

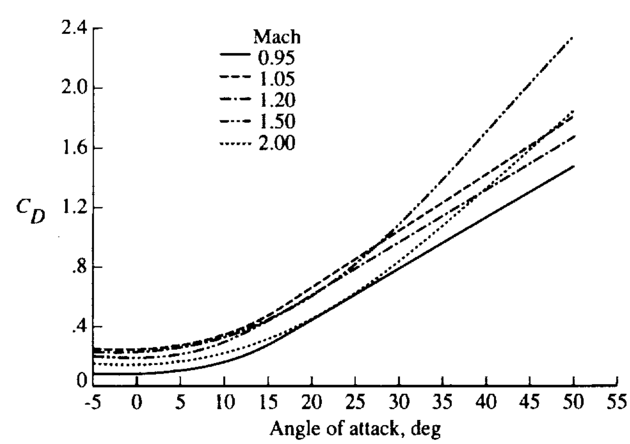

Figure D8. Drag coefficient variation for reference Shuttle II booster for Mach 0.95 to 2.00.

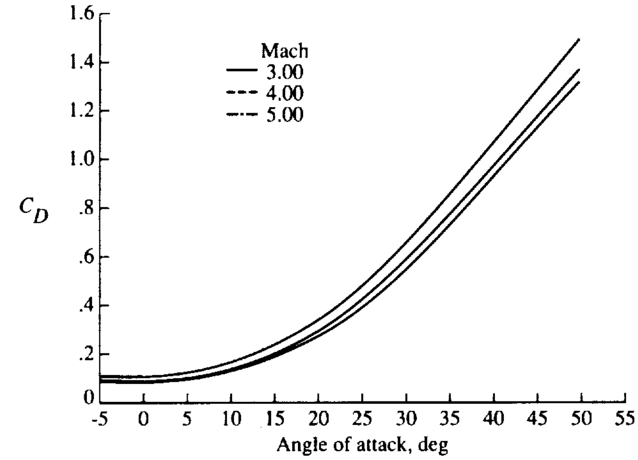

Figure D9. Drag coefficient variation for reference Shuttle II booster for Mach 3.00, 4.00, and 5.00.

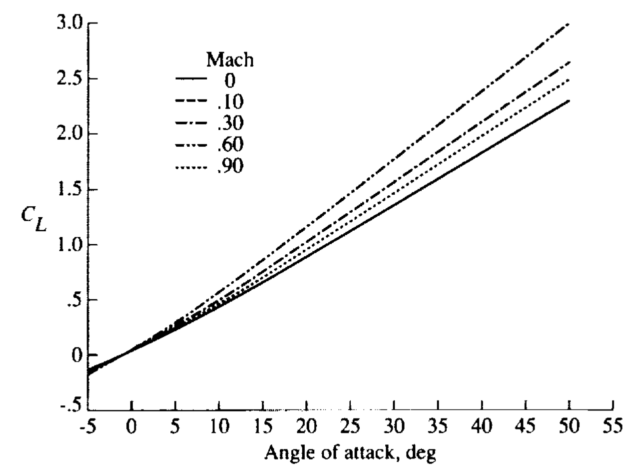

Figure D10. Lift coefficient variation for reference Shuttle II booster for Mach 0 to 0.90.

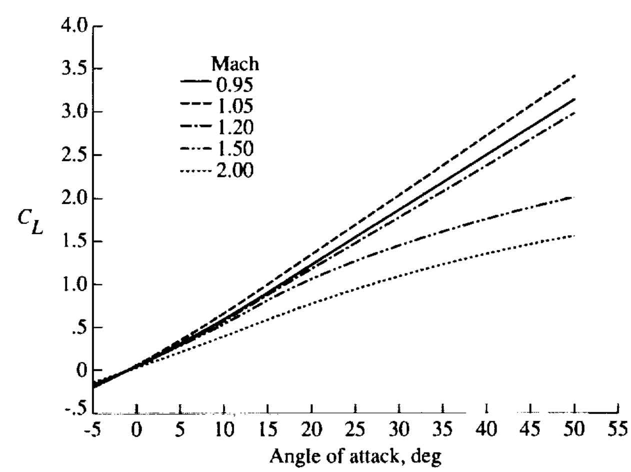

Figure D11. Lift coefficient variation for reference Shuttle II booster for Mach 0.95 to 2.00.

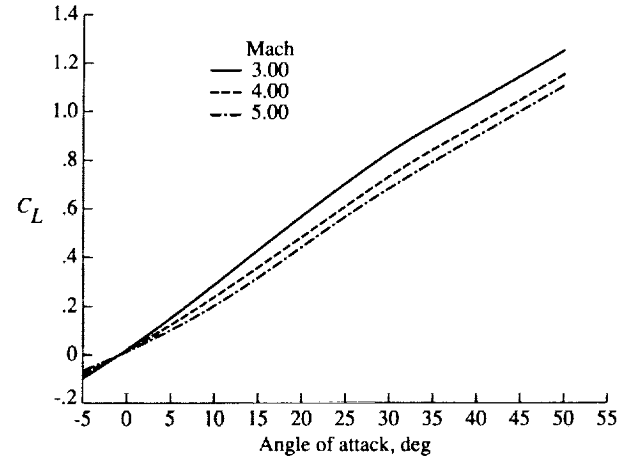

Figure D12. Lift coefficient variation for reference Shuttle II booster for Mach 3.00, 4.00, and 5.00.

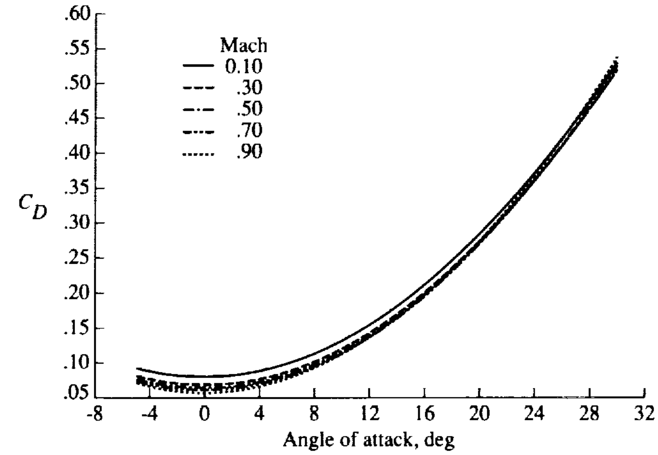

Figure D15. Lift coefficient variation for reference core vehicle for Mach 0.10 to 0.90.

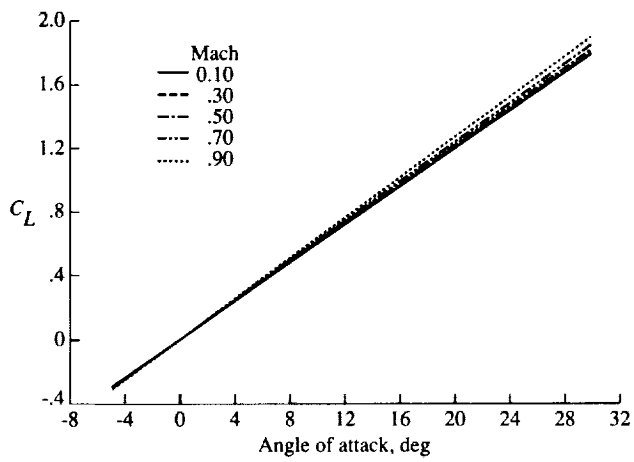

Figure D13. Lift coefficient variation for reference core vehicle for Mach 0.10 to 0.90.

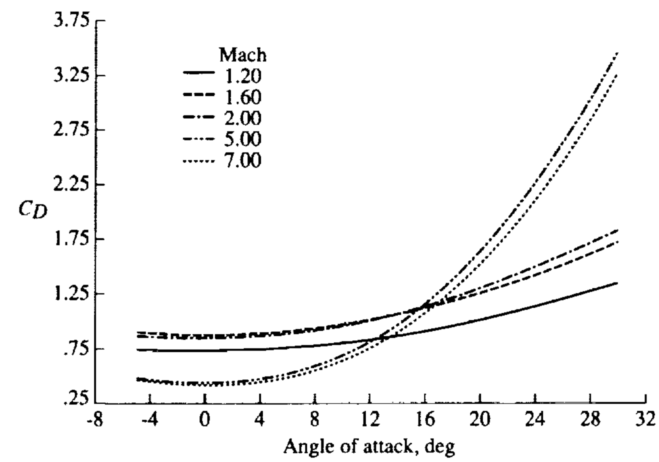

Figure D16. Drag coefficient variation for reference core vehicle for Mach 1.20 to 7.00.

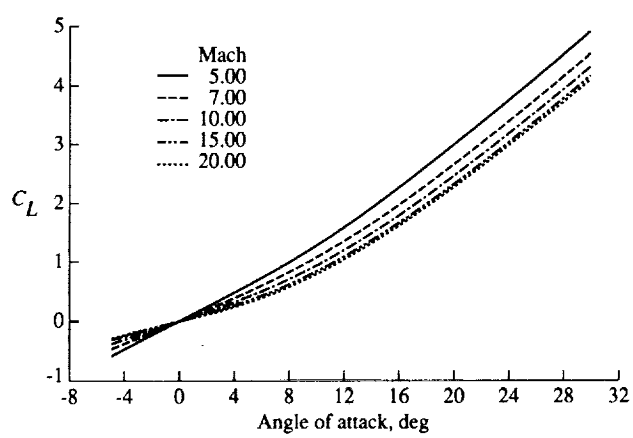

Figure D14. Lift coefficient variation for reference core vehicle for Mach 5.00 to 20.00.

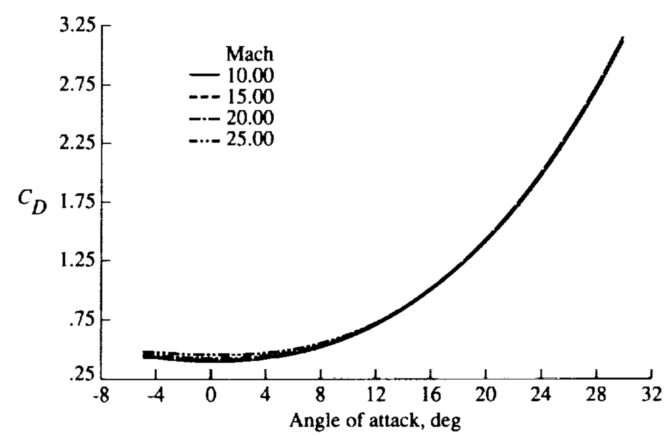

Figure D17. Drag coefficient variation for reference core vehicle for Mach 10.00 to 25.00.

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Report Documentation Page

1. Report No. NASA TP-3059	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Parametric Trade Studies on a Shuttle II Launch System Architecture		5. Report Date March 1991
		6. Performing Organization Code
7. Author(s) Douglas O. Stanley, Theodore A. Talay, Roger A. Lepsch, W. Douglas Morris, J. Christopher Naftel, and Christopher I. Cruz		8. Performing Organization Report No. L-16790
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No. 506-40-61-01
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report presents a series of trade studies conducted between 1986 and 1988 on a complementary architecture of launch vehicles as a part of a study often referred to as "Shuttle II." The results of the trade studies performed on the vehicles of a reference Shuttle II mixed-fleet architecture have provided an increased understanding of the relative importance of each of the major vehicle parameters. Among the parametric trade studies presented are trades on booster fuel type; lift-off thrust-to-weight ratio; staging Mach number; thrust split; crossfeed capability; engine-out capability; technology level; payload size; and target orbit inclination. This paper presents the reference Shuttle II vehicle concepts and the results of a series of parametric trade studies performed on those vehicles. In each trade discussed, special attention is given to the major vehicle performance and operational issues involved.

17. Key Words (Suggested by Authors(s)) Shuttle II Launch vehicles Architecture Heavy-lift vehicle Rocket-powered System studies	18. Distribution Statement Unclassified—Unlimited Subject Category 15

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 54	22. Price A04

NASA FORM 1626 OCT 86

NASA-Langley, 1991

For sale by the National Technical Information Service, Springfield, Virginia 22161-2171